Smithells Metals Reference Book

SEVENTH EDITION

EDITED BY
E.A. BRANDES & G.B. BROOK

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Seventh Edition

Edited by
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Preface to the Seventh Edition

This edition has been prepared with major assistance from co-editor G. B. Brook. The general presentation of previous editions has been retained and SI units have been used throughout.

The values for formulations given are selected by the contributors as the most reliable but for a particular review the reader should consult the references. In the case of mechanical properties data the values are for general guidance only; for design purposes it is essential to consult the relevant specifications.

To minimize bulk, the First Aid section has been omitted but a new chapter on related specifications has been added. Also added is a chapter on Metal-Matrix Composites.

The Equilibrium Diagrams section has been considerably updated and extended and the Magnetic Materials, Sintered Materials, Heat Treatment, Engineering Ceramics, Soldering and Brazing, Shape Memory, X-ray Analysis of Metallic Materials and Lasers have been rewritten.

Other chapters have been reviewed and updated as required.

E.A.B.
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1 Related specifications

Tables of related specifications are a guide to correspondence and should not be taken as exact equivalents. In all cases of doubt the national specification should be consulted. For more detail the references in some cases give more information.

Unified number designations –UNS are five-digit numbers prefixed by a letter that characterizes the alloy system as shown below.

UNS Letter Designation[1]

A Aluminium and aluminium alloys
C Copper and copper alloys
D Specified mechanical properties steels
E Rare earth and rare earth like metals and alloys
F Cast irons and cast steels
G AISI and SAE carbon and alloy steels
H AISI H-steels
J Cast steels (except tool steels)
K Miscellaneous steels and ferrous alloys
L Low melting metals and alloys
M Miscellaneous nonferrous metals and alloys
N Nickel and nickel alloys
P Precious metals and alloys
R Reactive and refractory metals and alloys
S Heat and corrosion resistant (stainless) steels
T Tool steels
W Welding filler metals

Related specifications for steels are given for seven countries in Table 1.1 with subsections for steels of different types. For cast aluminium alloys see Table 22.1 and for wrought aluminium alloys Table 1.2. Table 1.3 gives related copper alloy specifications subdivided into high-conductivity copper, brasses and nickel silvers. Magnesium cast and wrought are in Table 1.4, while for nickel alloys Table 22.26 and for titanium alloys Table 22.32 can be used.

Table 1.1 RELATED SPECIFICATIONS FOR STEEL

1.1.1 Carbon steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051-65*	*Sweden SIS*	*USSR GOST 1050-60*
C≤0.06 Mn<0.3	015A03	1005 (G10050)	Fd5	D6–2 (1.0314)	—	14 11 60	-
C≤0.08 Mn0.2/0.4	030A04	1006 (G10060)	—	D7–1 (1.0313)	—		-
C≤0.08 Mn0.1/0.4	040A04 (2A, 2B)	1008 (G10080)	FdTu2	UQ St36 (1.0204)	—	—	-
C≤0.08 Mn0.4/0.6	050A04	M1008 (G10080)	Fd3	U St14 (1.0336)	SPHT1	14 12 25	05kp
C0.08/0.13 Mn0.5/0.7	060A10	1011 (G10110)	XC10	U St36 (1.0203)	SBC	14 13 32	08

Table 1.1 RELATED SPECIFICATIONS OF STEEL—*continued*

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.1/0.15 Mn0.3/0.5	040A12	1012 (G10120)	XC12	Ck10 (1.1121)	—	—	—
C0.13/0.18 Mn0.7/0.9	080A15 080M15	1016 (G10160)	AF37C12	Rst44.2 (1.0419/01)	SM58	13 50	—
C0.15/0.2 Mn0.3/0.6	040A17	1017 (G10170)	XC18	Ck15 (1.1141)	—	—	—
C0.18/0.23 Mn0.4/0.6	050A20 (2C, 2D)	1020 (G10200)	C20	C22 (1.0402)	—	14 50	20
C0.25/0.3 Mn0.7/0.9	080A27 (5A)	1029 (G10290)	—	—	S28C	—	—
C0.28/0.3 Mn0.7/0.9	080A30 (5B)	1030 (G10300)	—	Cq35 (1.1172)	S30C	—	30/30G
C0.33/0.38 Mn0.7/0.9	080A35 (8A)	1035 (G10350)	XC32	Ck34 (1.1181)	S35C	15 72	35
C0.38/0.43 Mn0.7/0.9	080A40 (8C)	1040 (G10400)	XC42H1	Ck40 (1.1186)	S40C	—	40
C0.43/0.5 Mn0.6/1.0	080M46	1045 (G10450)	XC42H1 XC45	Ck45 (1.1191)	S45C	16 72	45
C0.45/0.55 Mn0.6/1.0	080M50	1050 (G10500)	—	Ck50 (1.1206)	—	—	50
C0.6/0.65 Mn0.5/0.7	080A62 (43D)	1060 (G10600)	XC60	Ck60 (1.1221)	S58C	16 78	60; 60G
C0.7/0.75 Mn0.7/0.9	080A72	1070 (G10700)	XC68	Ck67 (1.1231)	—	17 70	—
C0.7/0.9 Mn0.7/0.9	080A83	1080 (G10800)	XC75	Ck75 (1.1248)	—	17 74 17 78	—
C0.95/1.05 Mn0.5/0.7	060A99	1095	XC100	Ck101 (1.1274)	SUP4	18 70	—

1.1.2 Carbon-higher manganese steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.15/0.23 Mn1.0/1.4	120M19	1518 (G15180)	20M5	20Mn6 (1.1169)	SMnC420	—	18G2
C0.15/0.23 Mn1.35/1.7	150M19 (14A/14B)	1524 (G15240)	—	—	—	—	18G2S
C0.24/0.32 Mn1.0/1.4	120M28	1526 (G15260)	—	GS–24Mn4 (1.1136)	—	—	—
C0.24/0.32 Mn1.3/1.7	150M28 (14A/14B)	1527	20M5	20M6 (1.1170)	SCMn1	—	—
C0.32/0.40 Mn1.0/1.4	120M36 (15B)	1536 (G15360)	35M5	36Mn5 (1.1167)	2120	3562 35GL	—

1.1.3 Carbon-free cutting steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C<0.15 Mn0.9/1.3	220M07 (1A)	1212	S250	96Mn28 (1.01715)	SUM21	14 19 12	—
C<0.15 Mn1.1/1.5	240M07	—	S300Pb S300	96Mn36 (1.0736)	SUM25	—	—
C0.24/0.32 Mn1.1/1.5	216M28	—	—	—	SUM41	—	—

Table 1.1 RELATED SPECIFICATIONS OF STEEL—*continued*

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051-65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.32/0.4 Mn1.0/1.4	212M36 (8M)	1140 (G11400)	35MF36	35S20 (1.0726)	—	1957	—
C0.40/0.48 Mn1.0/1.4	212M44 (8M)	1144 (G11440)	45MF6	45S20 (1.0727)	—	1973	—

1.1.4 Direct-hardening alloy steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.36/0.44 Mn0.7/1.0 Ni0.7/1.0	503M40 (12)	—	40N3	—	—	—	—
C0.4/0.45 Mn0.7/1.0 Ni0.7/1.0	503M45 (12C)	—	40N3	—	—	—	—
C0.55/0.65 Mn0.5/0.8 Cr0.5/0.8	426M60 (11)	5160	—	—	—	—	—
C0.36/0.44 Mn0.6/0.9 Cr0.9/1.2	530M40 (18 & A–D)	5130/2/5 5140	32C4 38C4	38Cr2 (1.7033/5)	SCr2	14 22 45	30KHRA 35KHA 40KH
C0.95/1.1 Mn0.4/0.7 Cr1.2/1.6	535A99 (31)	E52100	100C6	100Cr2 (1.3505)	SCr5	14 22 58	KH SHKH15/R
C0.26/0.6 Mn1.3/1.7 Mo0.22/0.32	605M30/36 (16 & 16D) Water hardening	4032/7 (G40320/70)	18MD4.05	13MnMo6 5 (1.5426)	—	—	—
C0.36/0.44 Mn0.6/0.9 Cr0.5/0.8 Ni1.1/1.5	640M40 (111)	3140	—	40NiCr6	SNC1	—	40KHN
C0.33/0.44 Rest as 640M40	640A35	3130	30NC6	36NiCr6 (1.5710)	—	—	—
C0.27/0.35 Mn0.45/0.7 Cr0.9/1.2 Ni2.75/3.25	653M31 (23)	—	30NC11	31NiCr14 (1.5755)	—	14 25 34	30KHNBA
C0.36/0.44 Mn0.7/1.0 Cr0.9/1.2 Mo0.15/0.25	708M40 (19A)	4137/40	42CD4	42CrMo4 (1.7225)	—	14 22 34	35KHM
C0.35/0.4 Mn0.7/0.9 Cr0.9/1.2 Mo0.15/0.25	708A37 (19B)	4135/37	35CD4	CS-34CrMo4 (1.7220)	SCM3H	14 22 34	34KHN
C0.4/0.45 Mn0.75/1.0 Cr0.9/1.2 Mo0.15/0.25	708A42 (19C)	4142/48	42CD4	50CrMo4 (1.7228)	SCM4H	14 22 32	—
C0.2/0.28 Mn0.45/0.7 Cr3/3.5 Mo0.45/0.65	722M24 (40B)	—	30CD12	32CrMo12 (1.7361)	—	—	—

Table 1.1 RELATED SPECIFICATIONS OF STEEL *–continued*

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.36/0.44 Mn0.45/0.7 Cr1/1.4 Ni1.3/1.7 Mo0.1/0.2	816M40 (110)	4340	35NCD6	36CrNiMo4 (1.6511/82)	–	14 25 41	40KHMA
C0.36/0.44 Mn0.45/0.7 Cr1/1.4 Ni1.3/1.7 Mo0.2/0.35	817M40 (24)	-	–	34CrNiMo6 (1.6582)	SNCH9	–	40KNMNA
C0.27/0.35 Mn0.45/0.7 Cr0.5/0.8 Ni2.3/2.8 Mo0.45/0.65	826M31 (25)	—	—	32NiCrMo104 (1.6743)	SNCM2	–	38KHN3MA
C0.27/0.35 Mn0.45/0.7 Cr0.9/1.2 Ni2.75/3.25 Mo0.25/0.35	830M31 (27)	—	30NCD12/15	32NiCrMo145 (1.6746)	SNCM5	14 25 34	—
C0.26/0.34 Mn0.45/0.7 Cr1.1/1.4 Ni3.9/4.3 Mo0.2/0.35	835M30 (30B)	–	35NCD16	30NiCrMo166 (1.6747)	SMCM25	–	–
C0.27/0.35 Mn0.4/0.65 Cr1.4/1.8 Ni3.9/4.3 Al0.9/1.3	905M31 (41A) Nitriding	AMS6470E	30CAD6–12	34CrAl6 (1.8504)	–	14 29 40	38KHMYUA

1.1.5 Case hardening steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.12/0.17 Mn0.3/0.5 Cr0.3/0.5	523A14 (206)	5015	18C3	15Cr3 (1.7015)	G4104	—	—
C0.17/0.22 Mn0.7/0.9 Cr0.7/0.9	527A19 (207)	5120	18C3	20MnCr5 (1.7147)	SCr22	–	20KH
C0.14/0.2 Mn0.6/0.9 Cr0.6/1 Ni0.85/1.25	637M17 (352)	—	16NCD5	—	—	—	20KHN
C0.1/0.16 Mn0.35/0.6 Cr0.7/1 Ni3/3.75	655M13 (36A)	3316	12NC15	14NiCr14 (1.5752)	—	-	12KHN3A
C0.13/0.18 Mn0.3/0.5 Cr1/1.3 Ni3.9/4.3	659M15 (39A)	—	12NC15	14NiCr18 (1.5860)	—	—	-
C0.14/0.2 Mn0.35/0.75 Mo0.2/0.3 Ni1.5/2	655H17 (34)	4617	20NDB	—	—	14 25 20	15NMA
C0.2/0.26 Mn0.35/0.75 Mo0.2/0.3 Ni1.5/2.0	655A22 655M23 (35 & 35A)	4620	20NDB	–	—	–	20NM

Table 1.1 RELATED SPECIFICATIONS OF STEEL —*continued*

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.14/0.2 Mn0.6/0.95 Cr0.35/0.65 Mo0.15/0.25 Ni0.35/0.75	805M17 (361)	–	—	21NiCrMo2 (1.6523)	–		
C0.17/0.23 Mn0.6/0.95 Cr0.35/0.65 Mo0.15/0.25 Ni0.35/0.75	805M20 (362)	8620	20HCD2	21NiCrMo2 (1.6523)	—	–	–
C0.22/0.28 Mn0.6/0.95 Cr0.35/0.75 Mo0.15/0.25 Ni0.35/0.75	805M25 (363)	8622	–	21NiCrMo22 (1.6543)	–	—	—
C0.14/0.2 Mn0.6/0.9 Cr0.8/1.2 Mo0.1/0.2 Ni1.2/1.7	815M17 (353)	—	16NCDS	–	—	14 25 11	20KHN
C0.14/0.2 Mn0.6/0.9 Cr0.8/1.2 Mo0.1/0.2 Ni1.5/2	820M17 (354)	–	18NCD6	–	—	—	–
C0.1/0.16 Mn0.35/0.6 Cr0.7/1 Mo0.1/0.25 Ni3/3.75	832M13 (36C)	AMS6260E	—	14NiCrMo134 (1.6657)	SNCM5	–	—
C0.12/0.18 Mn0.25/0.5 Cr1/1.4 Mo0.15/0.3 Ni3.9/4.3	835M15 (39B)	—	–	15NiCrMo165 (1.6723)	SNCM25	–	—
C0.07/0.13 Mn0.3/0.6	045M10 (32A)	1009 1010 1012	XC10F C10D C12D	St 35.8 (1.0305) (1.0345)	—	14 13 31 14 13 32	10
C0.12/0.18 Mn0.6/1	080M15 (32C)	1015 1016	XC12F	– (1.0419)	S15C	14 13 70 14 21 01	146 156
C0.12/0.18 Mn0.9/1.3	210M15 (32M)	1114 1115	12MF4	– (1.0723)	—	14 19 22	–
C0.12/0.18 Mn1 1/1.5	130M15 (201)	–	—	–	–	14 14 31 14 14 32	146 156
C0.12/0.16 Mn1.2/1.6	214M15 (202)	1118	20MF4	—	—	14 14 22	—

1.1.6 Stainless, heat resisting and valve steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051 65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.12Max Mn0.5/2 Cr17/19 Ni8/11	302S25 (58A)	302	Z12CN18 10	X12CrNi18 8 (1.4300)	302	14 23 30 14 23 31	KH189NE
C0.12Max Mn1/2 Cr17/19 Ni8/11 S0.15/0.3	305S21 (58M)	303Se	Z10CN18–09	X12CrNiS18 8 (1.4305)	303Se	14 23 46	KH18N10E

Table 1.1 RELATED SPECIFICATIONS OF STEEL—*continued*

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.06Max Mn0.5/2 Cr17.5/19 Ni8/11	304S15 (58E)	304	Z6CN18–09	X5CrNi18 10 (1.4301)	304	14 23 33	0KH18N11
C0.07Max Mn0.5/2 Cr16.5/18.5 Ni9/11 Mo1.25/1.75	215S16 (58H)	—	—	X5CrNiMo1811 (1.4420)	—	14 23 40	—
C0.06Max Mn0.5/2 Cr16.5/18.5 Ni11/14 Mo2.25/3	320S17 (58J)	316	Z8CNDTi1712	X10CrNiMoTi (1.4571)	316	14 23 43	—
C0.4/0.5 Mn0.3/0.75 Si3/3.75 Cr7.5/9.5	401S45 (52)	—	—	X45SrSi93 (1.4718)	—	—	—
C0.09/0.15 Mn1Max Si0.8Max Cr11.5/13.5 Ni1Max	410S21 (56A)	410 S41000	Z10C13 12C13	G–X10Cr13 (1.4024)	410	–	EFCh13
C0.14/0.2 Mn1Max Si0.8Max Cr11.5/13.5 Ni1Max	420S29 (56B)	420 S42000	Z20C13	X20Cr13 (1.4021)	420J1	–	En25Ch12-40
C0.1Max Mn1Max Cr16/18 Ni0.5Max	430S15 (60)	430 S43000	Z15CN16–02	X6Cr17 (1.4016)	430	—	08Ch17T
C0.12/0.2 Mn1Max Cr15/18 Ni2/3	431S29 (57)	431 S43100	Z8CD17–01	X22CrNi17 (1.4057)	—	—	—

1.1.7 Carbon and alloy spring steels

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.5/0.55 Mn0.7/0.9	080A52 (43)	1050 1055	XC53	—	—	14 16 06	50, 55
C0.5/0.7 Mn0.7/0.9	080A67 (43E)	1065	XC65	C67 (1.0603)	—	—	65
C0.7/0.75 Mn0.6/0.8	070A72 (42)	1074 1080	XC80F	—	—	—	80
C0.5/0.57 Mn0.7/1 Si1.7/2.1	250A53 (45)	9255	5557	38Si7 (1/0970)	SUP6	14 20 90	55S2 55S9
C0.58/0.63 Mn0.7/1 Si1.7/2.1	250A61 (45A)	9260	—	— (1.0971)	SUP7	—	60S2A
C0.55/0.65 Mn0.1/1 Si0.1/0.35 Cr0.6/0.9	527A60 (48)	5147	50C4	—	SUP9	–	50CH

Table 1.1 RELATED SPECIFICATIONS OF STEEL – *continued*

Nominal composition	*UK BS970 (En)*	*USA AISI/SAE (UNS)*	*France AFNOR*	*W. Germany DIN (Wk No.)*	*Japan JIS G4051–65*	*Sweden SIS*	*USSR GOST 1050–60*
C0.46/0.54 Mn0.6/0.9 Si0.1/0.35 Cr0.8/1.1 V0.15Min	735A50 (47)	6150	50V4	50CrV4 (1.8159)	SUP10	14 22 30	50KHCA

Table 1.2 RELATED SPECIFICATIONS FOR WROUGHT ALUMINIUM ALLOYS

BS international	*Nominal composition old ISO No.* Al–	*UK former BS designation*	*France former NF*	*W. Germany Wk. No.*	*Canada*	*Sweden*	*USSR*
1050A	99.5	1B	A5	3.0255	–	4 007	–
1080A	99.8	1A	A8	3.0285	–	4 004	–
1200	99	1C	A4	3.0205	990	4 010	–
1350	99.5	1E	A5/6	3.0257	–	–	–
2011	Cu6BiPb	FC1	A–U5 PbBi	3.1655	CB60	4 355	–
2014A	Cu4SiMg	H15	A–U4SG	3.1255	CS41N	4 338	AK 8
2017A	Cu4MgSi	–	A–U4G	3.1325	–	–	–
2024	Cu4Mg1	2L97, 2L98, L109, L110, DTD5100A	A–U4G1	3.1355	CG42	–	D 16
2031	Cu2NiMgFeSi	H12	A–U2N	–	–	–	–
2117	Cu2Mg	3L86	A–U2G	3.1305	CG30	–	D 18
2618A	Cu2Mg1.5 Fe1Ni1	H16	A–U2GN	–	–	–	AK 4-1
3103	Mn1	N3	–	3.0515	–	4054	–
3105	MnMg	N31	–	3.0505	–	–	–
4043	Si5	N21	A–S5	–	–	–	–
4047	Si12	N2	A–S12	–	–	–	–
5005	Mg1	N41	A–G0.6	–	–	4106	–
5056A	Mg5	N6	A–G5M	3.3555	–	–	–
5083	Mg4.5Mn	N8	A–G4.5MC	3.3547	GM41	4140	–
5154A	Mg3.5	N5	–	–	GR40	–	AMG3
5251	Mg2	N4	A–G2M	3.3525	–	–	–
5454	Mg3.6	N51	A–G2.5MC	3.3537	GM31N	–	–
5554	Mg3Mn	N52	–	–	GM31P	–	–
6061	Mg1SiCu	H20	A–GSUC	3.3211	GS11N	–	AD3
6063	Mg0.5Si	H9	–	–	GS10	4104	AD31
6082	Si1MgMn	H30	A–SGM0.7	3.2315	–	4 212	–
7020	Zn4.5Mg	H17	A–Z5G	3.4335	–	4 425	–
7075	Zn6MgCu	2L95, L160, L161, L162	A–Z5GU	3.4365	ZG62	SM6958	V95

Table 1.3 RELATED SPECIFICATIONS FOR COPPER ALLOYS

1.3.1 High conductivity coppers

Nominal composition Cu	*UK BS*	*USA ASTM*	*France NF*	*W. Germany DIN (Wk No.)*	*Canada Cu-*	*Sweden Cu-*	*Italy Cu-*
(+Ag) 99.9 min	C101	ETP	Cu/a1	(2.0060)	ETP110	ETP	ETP
(+Ag) 99.9 min	C102	FRHC	Cu/a2	(2.0060)	FRHC	–	—
(+Ag) 99.85 min	C104	FRTP	Cu/a3	(2.0080)	FRTP125	FRTP	FRTP
(+Ag) 99.95 min	C103	OF	Cu/c1	(2.0070)	OF102	OF	OF
(+Ag) 99.9 min P	—	DLP	—	—	DLP120	—	DLP
(99.85) min P	C106	DHP	Cu/b	(2.0090)	DHP122	DHP	DHP
(+Ag) +As 99.7 min P, As	C107	DPA	—	(2.0150)	DPA142	—	DPA
(+Ag) 99.9 Ag	—	STP	—	(2.1202)	STP114	14 50 30	STP
(+Ag) 99.95 min Ag	—	OFS	—	SE-CuAg	—	—	—
Cd 0.7/1.3	C108	CuCd1	—	CuCd1	—	50 55	—
(+Ag) 99.9 Te 0.3/0.8	C109	No145	—	(2.1545) (2.1546)	—	—	—
Cr 0.5/1.2	A2/1	CuCr1	—	CuCr	—	—	—
Be 1.6/1.9 Co, Ni, Fe	CB101	CuBe1.7 CoNi	—	CuBe1.7	—	—	—
Be 1.8/2.1 Co, Ni, Fe	—	CuBe2CoNi	—	CuBe2	—	—	—
Co 2/2.8 Be, Fe, Ni	—	CuCo2Be	—	CuCoBe	—	—	—
Ni 1.6/2.5 Si	A3/2	CyNi2Si	—	CuNi2Si	—	—	—
Si 2.7/3.5 Mn 0.7/1.5	CS101	—	CuSi3Mn1	—	HC.S3	—	CuSi3Mn1

1.3.2 Brasses—copper zinc

Nominal composition Cu	*UK BS*	*USA ASTM*	*France NF*	*W. Germany DIN (Wk No.)*	*Japan JIS*	*Canada CSA*	*Sweden SIS*
Zn5	CZ125	210	—	2.0020	RBsP1, R1, W1	HC.Z5	—
Zn10	CZ101	220	U-Z10	2.0230	RBsP2, R2, W2, T2	HC.Z10	—
Zn15	CZ102	230	U-Z15	2.0240	RBsP3, W3, R3, T3	HC.Z15	14 51 12
Zn20	CZ103	240	—	2.0250	RBsP4, W4, R4	HC.Z20	14 51 14
Zn28/30	CZ105/6	260	U-Z30	2.0265	BsP1, W1, T1	HC.Z20	14 51 22
Zn33	CZ107	268, 270	U-Z33	2.0280	BsP2A, W2, R2A, T2	HC.Z34	14 51 24
Zn37	CZ108	272, 274	U-Z36	2.0320	BsP2B, R2B	HC.Z37	14 51 50
Zn40	CZ109	280	U-Z40	2.0360	BsP3, BF, W3, T3	—	—
Zn36Pb2	CZ119	353	U-Z36Pb2	2.0330	PbBsP, R, W11	HC.ZP352	51 40
Zn36Pb3	CZ124	360	U-Z36Pb3	2.0375	—	HC.ZP353	—
Zn40Pb	CZ123	365, 368	—	2.0370 2.0360	PbBsP1, R1, W1	HC.ZP391	51 63

Table 1.3 RELATED SPECIFICATIONS FOR COPPER ALLOYS – *continued*

Nominal composition Cu	*UK BS*	*USA ASTM*	*France NF*	*W. Germany DIN (Wk No.)*	*Japan JIS*	*Canada CSA*	*Sweden SIS*
Zn39Pb2	CZ120, 122	377	U-Z39Pb1	2.0380	PbBsP13, R13, W1	HC.ZP382	51 68
Zn40Pb3	CZ121	–	U-Z39Pb2	2.0405	–	–	51 70
Zn20Al2	CZ110	687	Cu-Zn22Al2	2.0460	BsTF2, 3, 4	HC.ZA202V687	52 17
Zn28Sn1	CZ111	442, 445	Cu-Zn29Sn1	2.0470	BsTF1	HC.ZT281V443, 445	52 20
Zn38Sn1	CZ112	462, 464–467, 482, 485	–	2.0530	NBsP1, B1, P2, B2,TP	HC.ZT391,464, 381, P482, ZP372T485	–

1.3.3 Nickel silvers – copper nickel zinc

Nominal composition Cu	*UK BS*	*USA ASTM*	*France NF*	*W. Germany DIN (Wk No.)*	*Japan JIS*	*Canada CSA*	*Sweden SIS*
Ni10Zn27	NS103	745	U-Z28n9	–	NSP4, NSR4, NSW4	HC.ZN2410 745	–
Ni12Zn24	NS104	757	–	CuNi12Zn24	NSP3, NSB3 NSR3, NSW3	HC.ZN2312 757	52 43
Ni15Zn21	NS105	–	U-Z22N15	–	NSP3, NSB3 NSR3, NSW3	–	–
Ni18Zn20	NS106	752	U-Z22N18	CuNi18Zn20	NSP2, NSB2 NSR2, NSW2	HC.NZ1817 752	52 46
Ni18Zn27	NS107	770	U-Z27N18 × 85	–	NSSP, NSBS NSSR, NSWS NSSPS, NSSRS	HC.ZN2718 770	–
Ni10Zn42Pb2	NS101	–	U-Z45N9	CuNi10Zn42Pb	–	–	–
Ni18Zn19Pb1	NS113	794	–	CuNi18Zn19Pb	PbNSB	–	–

Table 1.4 RELATED SPECIFICATIONS FOR MAGNESIUM ALLOYS

Cast alloys

Nominal composition	*UK designation*	*UK BS2970 MAG*	*USA ASTM*	*USA AMS*	*France AFNOR*	*Standard AECMA*	*W. Germany aircraft*	*W. Germany DIN 1729*
RE3Zn2.5 Zr0.6	ZRE1	6-TE	EZ33A-T5	4442B	G-TR3Z2	MG-C-91	3.6204	3.5103
Zn4.2RE1.3 Zr0.7	RZ5	5-TE	ZE41A-T5	4439A	G-Z4TR	MG-C-43	3.6104	3.5101
Th3Zn2.2 Zr0.7	ZT1	8-TE	HZ32A-T5	4447B	G-Th3Z2	MG-C-81	3.6254	3.5105
Zn5.5Th1.8 Zr0.7	TZ6	9-TE	ZH62A-T5	4438B	–	MG-C-41	3.5114	3.5102
Al8Zn0.5 Mn0.3	A8	1-M	AZ81A-F	–	G-A9	MG-C-61	–	3.5812
Al9.5Zn0.5 Mn0.3	AZ91	3-7B	AZ91C-T4	–	G-A9Z1	–	3.5194	–
Al7.5/9.5 Zn0.3/1.5 Mn0.15min	C	7-M	–	–	–	–	–	3.5912

1.4.2 Wrought alloys

Zn3Zr0.6	ZW3	E-151M	–	–	–	MG-P-43	–	–
Al6Zn1Mn0.3	AZM	E-121M	AZ61A-F	4350H	G-A6Z1	MG-P-63	W.3510	3.5612
Al8.5Zn0.5 Mn0.12min	AZ80	–	AZ80A	4360D	–	MG-P-61	W.3515	3.5812
Al3Zn1Mn0.3	AZ31	S-1110	AZ31B-0	4375F	G-A2Z1	MG-P-62	W.3504	3.5312

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2 Introductory tables

2.1 Conversion factors

Conversion factors into and from SI units are given in Table 2.5. The table can also be used to convert from one traditional unit to another. Convenient multiples or sub-multiples of SI units can be derived by the application of the prefix multipliers given in Table 2.4. Table 2.6 gives commonly required conversions.

The majority of the conversion factors are based upon equivalents given in BS 350:Part 1:1983 'Conversion Factors and Tables'.

Throughout the conversions the acceleration due to gravity (g) has been taken as the standard acceleration 9.806 65 $m s^{-1}$. Units containing the word force like 'pounds force' are converted to SI units using this value of g.

The B.t.u. conversions are based on the definition accepted by the 5th International Conference on Properties of Steam, London, 1956, that 1 B.t.u. $lb^{-1} = 2.326\ J g^{-1}$ exactly. Conversions to joules are given for three calories; calories (IC) is the 'international table calorie' redefined by the 1956 conference referred to above as 4.1868 J. Calories (15 °C) refers to the calorie defined by raising the temperature of water at 15 °C by 1 °C and calories (US thermochemical) is the 'defined' calorie used in some USA work and is defined at 4.184 J exactly.

The conversions are grouped in alphabetical order of the physical property to which they relate but are not alphabetical within the groups.

2.1.1 SI units

In this edition quantities are expressed in SI (Système International) units. Where c.g.s. units have been used previously only SI units are given. However, familiar units in general technical use have been retained where they bear a simple power of ten relation to the strict SI unit. For instance density is given as $g cm^{-3}$ and not as $kg m^{-3}$. Where Imperial units have been used (e.g. in Mechanical Properties, etc.) data are given in both SI units and Imperial units.

The basic units of the SI system are given in Table 2.1, derived units with special names and symbols in Table 2.2 and derived units without special names in Table 2.3.

Multiples and sub-multiples of SI units are formed by prefixes to the name of the unit. The prefixes are shown in Table 2.4. The prefixed unit is written without a hyphen — for instance a thousand million newtons is written giganewton — symbol GN. The name of the unit is written with a small letter even when the symbol has a capital letter, e.g. ampere, symbol A. In the case of the kilogram, the multiple or sub-multiple is applied to the gram — for instance a thousand kilograms is written Mg.

In this edition stress is expressed in Pascals (Pa). A pascal (Pa) is identical to a newton per square metre ($N m^{-2}$) and a megapascal (MPa) is identical to a newton per square millimetre ($N mm^{-2}$).

PRINTED FORM OF UNITS AND NUMBERS

The symbol for a unit is in upright type and unaltered by the plural. It is not followed by a full stop unless it is at the end of a sentence. Only symbols of units derived from proper names are in the upper case.

When units are multiplied they will be printed with a space between them. Negative indices are

used for units expressed as a quotient. Thus newtons per square metre will be $N\,m^{-2}$ and metres per second will be $m\,s^{-1}$.

The prefix to a unit symbol is written before the unit symbol without a space between and a power index applies to both the symbols. Thus square centimetres is cm^2 and not $(cm)^2$.

Numbers are printed with the decimal point as a full stop. For long numbers, a space and not a comma is given between every three digits. For example $\pi = 3.141\,592\,653$. When a number is entirely decimal it will begin with a zero, e.g. 0.5461. If two numbers are multiplied, a × sign is used as the operator.

HEADING OF COLUMNS IN TABLES AND LABELLING OF GROUPS

The rule adopted in this edition is that the quantity is obtained by multiplying the unit and its multiple given at the column head by the number in the table.

For example when tabulating a stress of 2×10^5 Pa the heading is stress, below which appears 10^5 Pa, with 2.0 appearing in the table. If no units are given in the column heading, the values given are numbers only. In graphs the power of ten and units by which the point on the graph must be multiplied are given on the axis label.

TEMPERATURES

The temperature scale IPTS–68 has been replaced by the International Temperature Scale of 1990 (ITS–90). For details of this see chapter 16, where Table 16.1 gives the differences between ITS–90 and EPT–76 and between ITS–76 and between ITS–90 and IPTS–68. Figure 16.1 gives differences $(t_{90} - t_{68})$ between ITS-90 and IPTS–68 in the range −260°C to 1064°C. Table 2.7 gives conversions between the old IPTS–68 and the old IPTS–48.

Table 2.1 BASIC SI UNITS

Quantity	*Name of unit*	*Unit symbol*
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Luminous intensity	candela	cd
Amount of substance	mole	mol
Plane angle	radian	rad
Solid angle	steradian	sr

From 'Quantities, Units and Symbols', Royal Society, 1981.

Table 2.2 DERIVED SI UNITS WITH SPECIAL NAMES

Quantity	*Name of unit*	*Symbol*	*Equivalent*	*Definition*
Activity (radioactivity)	becquerel	Bq	s^{-1}	
Absorbed dose (of radiation)	gray	Gy	$J\,kg^{-1}$	
Dose equivalent (of radiation)	sievert	Sv	$J\,kg^{-1}$	
Energy	joule	J	N m	$m^2\,kg\,s^{-2}$
Force	newton	N	$J\,m^{-1}$	$m\,kg\,s^{-2}$
Stress or pressure	pascal	Pa	$N\,m^{-2}$	$m^{-1}\,kg\,s^{-2}$
Power	watt	W	$J\,s^{-1}$	$m^2\,kg\,s^{-3}$
Electric charge	coulomb	C	A s	s A
Electric potential	volt	V	$W\,A^{-1}$	$m^2\,kg\,s^{-3}\,A^{-1}$
Electric resistance	ohm	Ω	$V\,A^{-1}$	$m^2\,kg\,s^{-3}\,A^{-2}$
Electric capacitance	farad	F	$C\,V^{-1}$	$m^{-2}\,kg^{-1}\,s^4\,A^2$
Electric conductance	siemens	S	$A\,V^{-1}$	$m^{-2}\,kg^{-1}\,s^3\,A^2$
Magnetic flux	weber	Wb	V s	$m^2\,kg\,s^{-2}\,A^{-1}$

Table 2.2 DERIVED SI UNITS WITH SPECIAL NAMES—*continued*

Quantity	*Name of unit*	*Symbol*	*Equivalent*	*Definition*
Inductance	henry	H	$V s A^{-1}$	$m^2 kg s^{-2} A^{-2}$
Magnetic flux density	tesla	T	$Wb m^{-2}$	$kg s^{-2} A^{-1}$
Luminous flux	lumen	lm	cd sr	cd sr
Illumination	lux	lx	cd sr m^{-2}	m^{-2} cd sr
Frequency	hertz	Hz	s^{-1}	s^{-1}

From 'Quantities, Units and Symbols', Royal Society, 1981.
Note: Symbols derived from proper names begin with a capital letter.
In the definition the steradian (sr) is treated as a base unit.

Table 2.3 SOME DERIVED SI UNITS WITHOUT SPECIAL NAMES

Quantity	*SI unit*	*Symbol*
Area	square metre	m^2
Acceleration	metre/second squared	$m s^{-2}$
Angular velocity	radian/second	$rad s^{-1}$
Calorific value	joule/kilogram	$J kg^{-1}$
Concentration	mole/cubic metre	$mol m^{-3}$
Current density	ampere/square metre	$A m^{-2}$
Density	kilogram/cubic metre	$kg m^{-3}$
Diffusion coefficient	square metre/second	$m^2 s^{-1}$
Electrical conductivity	siemens/metre	$S m^{-1}$
Electric field strength	volt/metre	$V m^{-1}$
Electrical resistivity	ohm metre	Ωm
Entropy	joule/kelvin	$J K^{-1}$
Exposure (to radiation)	coulomb/kilogram	$C kg^{-1}$
Heat capacity	joule/kelvin	$J K^{-1}$
Heat flux density	watt/square metre	$W m^{-2}$
Latent heat	joule/kilogram	$J kg^{-1}$
Luminance	candela/square metre	$cd m^{-2}$
Magnetic field strength	ampere/metre	$A m^{-1}$
Magnetic moment	joule/tesla	$J T^{-1}$
Molar volume	cubic metre/mole	$m^3 mol^{-1}$
Moment of inertia	kilogram/square metre	$kg m^{-2}$
Moment of force	newton metre	N m
Molar heat capacity	joule/kelvin mole	$J K^{-1} mol$
Permittivity	farad/metre	$F m^{-1}$
Permeability	henry/metre	$H m^{-1}$
Radioactivity	1/second	s^{-1}
Speed (velocity)	metre/second	$m s^{-1}$
Specific volume	cubic metre/kilogram	$m^3 kg^{-1}$
Specific heat-mass	joule/kilogram kelvin	$J kg^{-1} K^{-1}$
Specific heat-volume	joule/cubic metre kelvin	$J m^{-3} K^{-1}$
Surface tension	newton/metre	$N m^{-1}$
Thermal conductivity	watt/metre kelvin	$W m^{-1} K^{-1}$
Thermoelectric power	volt/kelvin	$V K^{-1}$
Viscosity–kinematic	square metre/second	$m^2 s^{-1}$
Viscosity–dynamic	pascal second	Pa s
Volume	cubic metre	m^3
Wave number	1/metre	m^{-1}

Table 2.4a PREFIXES FOR MULTIPLES AND SUB-MULTIPLES USED IN THE SI SYSTEM OF UNITS

Sub-multiple	*Prefix*	*Symbol*	*Multiple*	*Prefix*	*Symbol*
10^{-1}	deci	d	10	deca	da
10^{-2}	centi	c	10^2	hecto	h
10^{-3}	milli	m	10^3	kilo	k
10^{-6}	micro	μ	10^6	mega	M
10^{-9}	nano	n	10^9	giga	G
10^{-12}	pico	p	10^{12}	tera	T
10^{-15}	femto	f	10^{15}	peta	P
10^{-18}	atto	a	10^{18}	exa	E

From 'Quantities, Units and Symbols', Royal Society, 1981.

Table 2.5 CONVERSION FACTORS

To convert B to A multiply by	*A*	*B*	*To convert A to B multiply by*
	Acceleration		
10^{2}	centimetres/second squared	metres/second squared	10^{-2}
$3.937\,008 \times 10$	inches/second squared	metres/second squared	2.54×10^{-2}
3.280 84	feet/second squared	metres/second squared	3.048×10^{-1}
$1.019\,716 \times 10^{-1}$	standard acceleration due to gravity	metres/second squared	9.806 65
	Angle—plane		
$2.062\,65 \times 10^{5}$	seconds	radians	$4.848\,14 \times 10^{-6}$
$3.437\,75 \times 10^{3}$	minutes	radians	$2.908\,88 \times 10^{-4}$
$5.729\,58 \times 10$	degrees	radians	$1.745\,33 \times 10^{-2}$
$1.591\,55 \times 10^{-1}$	revolutions	radians	6.283 19
$6.366\,20 \times 10$	grades	radians	$1.570\,80 \times 10^{-2}$
	Angular velocity		
$5.729\,58 \times 10$	degrees/second	radians/second	$1.745\,33 \times 10^{-2}$
$1.591\,55 \times 10^{-1}$	revolutions/second	radians/second	6.283 19
$3.437\,75 \times 10^{3}$	degrees/minute	radians/second	$2.908\,88 \times 10^{-4}$
9.549 27	revolutions/minute	radians/second	$1.047\,20 \times 10^{-1}$
	Area		
10^{28}	barn	square metres	10^{-28}
$1.550\,003 \times 10^{3}$	square inches	square metres	$6.451\,6 \times 10^{-4}$
$1.076\,391 \times 10$	square feet	square metres	$9.290\,3 \times 10^{-2}$
1.195 990	square yards	square metres	$8.361\,27 \times 10^{-1}$
$3.861\,02 \times 10^{-7}$	square miles	square metres	$2.589\,99 \times 10^{6}$
$2.471\,052 \times 10^{-4}$	acres	square metres	$4.046\,86 \times 10^{3}$
10^{-4}	hectares	square metres	10^{4}
2.471 052	acres	hectares	$4.046\,86 \times 10^{-1}$
2.5×10^{-1}	acres	roods	4
$1.562\,5 \times 10^{-3}$	square miles	acres	6.40×10^{2}
	Calorific value—volume basis		
$2.683\,92 \times 10^{-2}$	British thermal units/cubic foot	joules/cubic metre	$3.725\,89 \times 10$
$4.308\,86 \times 10^{-11}$	therms/UK gallon	joules/cubic metre	$2.320\,80 \times 10^{10}$
$2.388\,46 \times 10^{-4}$	kilocalories/cubic metre	joules/cubic metre	$4.186\,8 \times 10^{3}$
	Calorific value—mass basis		
4.299×10^{-4}	British thermal units/pound	joules/kilogram	2.326×10^{3}
$2.388\,46 \times 10^{-4}$	International kilocalories/kilogram	joules/kilogram	$4.186\,8 \times 10^{3}$
$2.390\,06 \times 10^{-4}$	thermochemical kilocalories/kilogram	joules/kilogram	4.184×10^{3}
	Compressibility		
10^{-1}	square centimetres/dyne	metres/newton	10
	Density		
10^{-3}	grams/cubic centimetre	kilograms/cubic metre	10^{3}
$1.603\,59 \times 10^{-1}$	ounces/gallon (UK)	kilograms/cubic metre	6.236 03
$6.242\,80 \times 10^{-2}$	pounds/cubic foot	kilograms/cubic metre	$1.601\,85 \times 10$
$3.612\,73 \times 10^{-5}$	pounds/cubic inch	kilograms/cubic metre	$2.767\,99 \times 10^{4}$
$1.002\,241 \times 10^{-2}$	pounds/gallon (UK)	kilograms/cubic metre	$9.977\,64 \times 10$
$8.345\,434 \times 10^{-3}$	pounds/gallon (US)	kilograms/cubic metre	$1.198\,26 \times 10^{2}$
$7.015\,673 \times 10$	grains/gallon (UK)	kilograms/cubic metre	$1.425\,38 \times 10^{-2}$
	Diffusion coefficient		
10^{4}	square centimetres/second	square metres/second	10^{-4}
	Electric charge		
$2.997\,93 \times 10^{9}$	electrostatic units	coulombs	$3.335\,64 \times 10^{-10}$
10^{-1}	electromagnetic units	coulombs	10

Table 2.5 CONVERSION FACTORS— *continued*

To convert B to A multiply by	*A*	*B*	*To convert A to B multiply by*
		Electric current	
$2.997\,93 \times 10^{9}$	electrostatic units	amperes	$3.335\,64 \times 10^{-10}$
10^{-1}	electromagnetic units	amperes	10
		Electric current density	
$2.997\,93 \times 10^{5}$	electrostatic units	amperes/square metre	$3.335\,64 \times 10^{-6}$
10^{-5}	electromagnetic units	amperes/square metre	10^{5}
10^{-4}	amperes/square centimetre	amperes/square metre	10^{4}
6.452×10^{-4}	amperes/square inch	amperes/square metre	1.55×10^{3}
$9.290\,2 \times 10^{-2}$	amperes/square foot	amperes/square metre	$1.076\,4 \times 10$
		Energy—work—heat	
$2.777\,778 \times 10^{-7}$	kilowatt hours	joules	3.6×10^{6}
$1.019\,72 \times 10^{-1}$	kilogram force metres	joules	9.806 65
$2.373\,04 \times 10$	foot poundals	joules	$4.214\,01 \times 10^{-2}$
$7.375\,62 \times 10^{-1}$	foot pounds force	joules	1.355 82
$3.725\,06 \times 10^{-7}$	horsepower hours	joules	$2.684\,52 \times 10^{6}$
$9.869\,23 \times 10^{-3}$	litre (dm^3) atmospheres	joules	$1.013\,25 \times 10^{2}$
$2.388\,46 \times 10^{-4}$	kilocalories (IC)	joules	$4.186\,8 \times 10^{3}$
8.850 34	inch pounds force	joules	$1.129\,9 \times 10^{-1}$
$9.478\,17 \times 10^{-4}$	British thermal units	joules	$1.055\,06 \times 10^{3}$
10^{7}	ergs	joules	10^{-7}
$6.241\,808 \times 10^{18}$	electron volts	joules	$1.602\,1 \times 10^{-19}$
$9.478\,13 \times 10^{-9}$	therms (Btu)	joules	$1.055\,06 \times 10^{8}$
$2.388\,46 \times 10^{-1}$	calories (IC)	joules	4.186 8
$2.389\,201 \times 10^{-1}$	calories (15°C)	joules	4.185 5
$2.390\,057 \times 10^{-1}$	calories (US thermochemical)	joules	4.184
		Entropy	
$2.388\,46 \times 10^{-1}$	calories (IC)/degree centigrade	joules/kelvin	4.186 8
$5.265\,62 \times 10^{-4}$	British thermal unit/degree Fahrenheit	joules/kelvin	$1.899\,11 \times 10^{3}$
		Force	
10^{5}	dynes	newtons	10^{-5}
3.596 94	ounces force	newtons	0.278 014
$1.019\,72 \times 10^{2}$	grams force	newtons	$9.806\,65 \times 10^{-3}$
$2.248\,09 \times 10^{-1}$	pounds force	newtons	4.448 22
7.233 01	poundals	newtons	0.138 255
$1.003\,61 \times 10^{-4}$	UK tons force	newtons	$9.964\,02 \times 10^{3}$
$1.124\,047 \times 10^{-4}$	US tons force	newtons	$8.896\,422 \times 10^{3}$
$1.019\,72 \times 10^{-1}$	kilograms force	newtons	9.806 65
		Fracture toughness	
$1.019\,72 \times 10^{-4}$	(kilograms force/square centimetre)$\sqrt{}$(centimetre)	newtons/$\sqrt{}$(metre^3)	$9.806\,55 \times 10^{3}$
$9.100\,42 \times 10^{-7}$	(kilopounds force/square inch) $\sqrt{}$(inch)	newtons/$\sqrt{}$(metre^3)	$1.098\,85 \times 10^{6}$
$4.062\,73 \times 10^{-7}$	(tons force/square inch)$\sqrt{}$(inch)	newtons/$\sqrt{}$(metre^3)	$2.461\,4 \times 10^{6}$
$3.162\,26 \times 10^{-6}$	hectobars$\sqrt{}$(millimetre)	newtons/$\sqrt{}$(metre^3)	$3.162\,3 \times 10^{5}$
		Heat—see *Energy*	
		Heat flow rate—see *Power*	
		Latent heat	
$4.299\,23 \times 10^{-4}$	British thermal units/pound	joules/kilogram	2.326×10^{3}
$2.388\,46 \times 10^{-4}$	calories (IC)/gram	joules/kilogram	$4.186\,8 \times 10^{3}$
$3.345\,52 \times 10^{-1}$	foot pounds force/pound	joules/kilogram	2.989 07
$1.019\,72 \times 10^{-1}$	kilogram force metres/kilogram	joules/kilogram	9.806 65

Table 2.5 CONVERSION FACTORS—*continued*

To convert B to A multiply by	*A*	*B*	*To convert A to B multiply by*
		Leak rate	
$7.500\,64 \times 10^{3}$	lusec (micron Hg litre/second)	joules/second	$1.333\,22 \times 10^{-4}$
		Length	
10^{10}	angstroms (Å)	metres	10^{-10}
10^{6}	microns (μ)	metres	10^{-6}
$9.979\,84 \times 10^{9}$	kx units	metres	$1.002\,02 \times 10^{-10}$
$3.937\,01 \times 10$	inches	metres	2.54×10^{-2}
3.280 84	feet	metres	3.048×10^{-1}
1.093 61	yards	metres	9.144×10^{-1}
$6.213\,71 \times 10^{-4}$	miles	metres	$1.609\,344 \times 10^{3}$
$5.396\,118 \times 10^{-4}$	miles (naut UK)	metres	$1.853\,184 \times 10^{3}$
$5.399\,568 \times 10^{-4}$	miles (naut Int)	metres	1.852×10^{3}
$1.8\dot{1} \times 10^{-1}$	rods, poles or perches	yards	5.5
2.5×10^{-1}	chains	rods, poles, etc.	4.0
10^{-1}	furlongs	chains	10.0
1.25×10^{-1}	miles (UK)	furlongs	8.0
$1.\dot{6}\dot{6} \times 10^{-1}$	fathoms	feet	6.0
$8.\dot{3}\dot{3} \times 10^{-3}$	cable lengths	fathoms	1.2×10^{2}
$1.644\,7 \times 10^{-4}$	nautical miles	feet	6.080×10^{3}
$1.893\dot{9} \times 10^{-4}$	miles (UK)	feet	5.280×10^{3}
		Magnetic conversions—see Magnetic units and conversion factors, chapter 20	
		Moment of force—see Energy	
		Moment of inertia	
10^{7}	grams centimetre squared	kilograms metre squared	10^{-7}
$3.417\,17 \times 10^{3}$	pounds inch squared	kilograms metre squared	$2.926\,40 \times 10^{-4}$
$2.373\,04 \times 10$	pounds foot squared	kilograms metre squared	$4.214\,01 \times 10^{-2}$
$5.467\,47 \times 10^{4}$	ounces inch squared	kilograms metre squared	$1.829\,00 \times 10^{-5}$
		Momentum	
7.233 01	foot pounds/second	kilogram metres/second	$1.382\,55 \times 10^{-1}$
10^{5}	gram centimetres/second	kilogram metres/second	10^{-5}
		Mass	
$5.643\,819 \times 10^{2}$	drams (Av)	kilograms	$1.771\,85 \times 10^{-3}$
$3.527\,399 \times 10$	ounces (Av)	kilograms	$2.834\,95 \times 10^{-2}$
2 204 622 6	pounds (Av)	kilograms	$4.535\,923\,7 \times 10^{-1}$
$1.574\,731 \times 10^{-1}$	stones (Av)	kilograms	6.350 293
$7.873\,650 \times 10^{-2}$	quarters (Av)	kilograms	$1.270\,059 \times 10$
$1.968\,415 \times 10^{-2}$	hundredweights (Av)	kilograms	$5.080\,23 \times 10$
$9.842\,035 \times 10^{-4}$	tons (Av)	kilograms	$1.016\,05 \times 10^{3}$
$1.543\,236 \times 10^{4}$	grains or minims (Apoth)	kilograms	$6.479\,89 \times 10^{-5}$
$7.716\,180 \times 10^{2}$	scruples (Apoth)	kilograms	$1.295\,978 \times 10^{-3}$
$2.572\,063 \times 10^{2}$	drams (Apoth)	kilograms	$3.887\,93 \times 10^{-3}$
$3.215\,072 \times 10$	ounces (Apoth or Troy)	kilograms	$3.110\,35 \times 10^{-2}$
$1.543\,237 \times 10^{4}$	grains (Troy)	kilograms	$6.479\,885 \times 10^{-5}$
10^{-3}	tonnes (metric)	kilograms	10^{3}
$1.102\,311 \times 10^{-3}$	tons (short 2000 lb)	kilograms	$9.071\,85 \times 10^{2}$
5.0×10^{3}	metric carats (CM)	kilograms	2.0×10^{-4}
		Mass per unit area	
$8.921\,80 \times 10^{3}$	pounds/acre	kilograms/square metre	$1.120\,85 \times 10^{-4}$
1.843 348	pounds/square yard	kilograms/square metre	$5.424\,912 \times 10^{-1}$
$2.048\,16 \times 10^{-1}$	pounds/square foot	kilograms/square metre	4.882 432
$2.949\,357 \times 10$	ounces/square yard	kilograms/square metre	$3.390\,57 \times 10^{-2}$
3.227 055	ounces/square foot	kilograms/square metre	$3.051\,52 \times 10^{-1}$

Table 2.5 CONVERSION FACTORS--*continued*

To convert B to A multiply by	*A*	*B*	*To convert A to B multiply by*
		Mass per unit length	
$5.599\,73 \times 10^{-2}$	pounds/inch	kilograms/metre	$1.785\,80 \times 10$
$6.719\,71 \times 10^{-1}$	pounds/foot	kilograms/metre	1.488 16
2.015 91	pounds/yard	kilograms/metre	$4.960\,55 \times 10^{-1}$
		Power—Heat flow rate	
10^{7}	ergs/second	watts	10^{-7}
3.412 14	British thermal units/hour	watts	$2.930\,71 \times 10^{-1}$
$8.598\,45 \times 10^{-1}$	kilocalories (IC)/hour	watts	1.163
$7.375\,61 \times 10^{-1}$	foot pounds force/second	watts	1.355 82
$2.388\,46 \times 10^{-1}$	calories (IC)/second	watts	4.186 8
$1.341\,022 \times 10^{-3}$	horsepower	watts	7.457×10^{2}
$1.359\,62 \times 10^{-3}$	metric horsepower (CV) (PS)	watts	$7.354\,99 \times 10^{2}$
		Pressure—see Stress	
		Radioactivity	
2.7×10^{-11}	curie	becquerel	3.7×10^{10}
		Radiation-absorbed dose	
10^{2}	rem	sievert	10^{-2}
		Radiation exposure	
3.876×10^{3}	roentgen	coulomb/kilogram	2.58×10^{-4}
		Specific heat capacity—mass basis	
10^{-3}	joules/gram degree centigrade	joules/kilogram kelvin	10^{3}
$2.388\,46 \times 10^{-4}$	calories*/gram degree centigrade	joules/kilogram kelvin	$4.186\,8 \times 10^{3}$
$2.388\,46 \times 10^{-4}$	British thermal units/ pound degree Fahrenheit	joules/kilogram kelvin	$4.186\,8 \times 10^{3}$
$1.858\,63 \times 10^{-1}$	foot pounds force/ pound degree Fahrenheit	joules/kilogram kelvin	5.380 32
$1.019\,72 \times 10^{-1}$	kilogram force metres/ kilogram degree centigrade	joules/kilogram kelvin	9.806 65
		Specific heat—volume basis	
10^{-6}	joules/cubic centimetre degree centigrade	joules/cubic metre kelvin	10^{6}
$2.388\,459 \times 10^{-4}$	kilocalories*/cubic metre degree centigrade	joules/cubic metre kelvin	$4.186\,8 \times 10^{3}$
$1.491\,066 \times 10^{-5}$	British thermal units/cubic foot degree Fahrenheit	joules/cubic metre kelvin	$6.706\,61 \times 10^{4}$
		Stress	
$1.450\,377 \times 10^{-4}$	pounds force/square inch	newtons/square metre	$6.894\,76 \times 10^{3}$
$6.474\,881 \times 10^{-8}$	UK tons force/square inch	newtons/square metre	$1.544\,43 \times 10^{7}$
10	dynes/square centimetre	newtons/square metre	10^{-1}
10^{-5}	bars	newtons/square metre	10^{5}
10^{-7}	hectobars	newtons/square metre	10^{7}
$1.019\,716 \times 10^{-7}$	kilograms force/square millimetre	newtons/square metre	$9.806\,65 \times 10^{6}$
$7.500\,638 \times 10^{-3}$	torrs	newtons/square metre	$1.333\,22 \times 10^{2}$
$7.500\,638 \times 10^{-3}$	millimetres of mercury	newtons/square metre	$1.333\,22 \times 10^{2}$
7.500 638	micron of mercury	newtons/square metre	$1.333\,22 \times 10^{-1}$
$9.869\,233 \times 10^{-6}$	atmospheres	newtons/square metre	$1.013\,250 \times 10^{5}$
1	pascals	newtons/square metre	1
$6.474\,8807 \times 10^{-2}$	UK tons force/square inch	megapascals	$1.544\,43 \times 10$
		Surface tension	
10^{3}	dynes/centimetre	newtons/metre	10^{-3}
$6.852\,178 \times 10^{-2}$	pounds force/foot	newtons/metre	$1.459\,39 \times 10$
$5.710\,148 \times 10^{-3}$	pounds force/inch	newtons/metre	$1.751\,268 \times 10^{2}$
		Temperature interval	
1	degrees Celsius (centigrade)	kelvins	1

*International calories.

Table 2.5 CONVERSION FACTORS—*continued*

To convert B to A multiply by	*A*	*B*	*To convert A to B multiply by*
1.8	degrees Fahrenheit	kelvins	$5.5\dot{5} \times 10^{-1}$
1.8	degrees Rankine	kelvins	$5.5\dot{5} \times 10^{-1}$
	Thermal conductivity		
10^{-2}	watts/centimetre degree centigrade	watts/metre kelvin	10^{2}
$2.388\,46 \times 10^{-3}$	calories/centimetre second degree centigrade	watts/metre kelvin	$4.186\,8 \times 10^{2}$
$8.598\,45 \times 10^{-1}$	kilocalories/metre hour degree centigrade	watts/metre kelvin	1.163
$5.777\,91 \times 10^{-1}$	British thermal unit/foot hour degree Fahrenheit	watts/metre kelvin	1.730 73
6.933 47	British thermal unit inch/square foot hour degree Fahrenheit	watts/metre kelvin	$1.442\,28 \times 10^{-1}$
	Time		
$1.6\dot{6} \times 10^{-2}$	minutes	seconds	6.0×10
$2.7\dot{7} \times 10^{-4}$	hours	seconds	3.600×10^{3}
$1.157\,41 \times 10^{-5}$	days	seconds	8.64×10^{4}
$1.653\,44 \times 10^{-6}$	weeks	seconds	6.048×10^{5}
$3.170\,98 \times 10^{-8}$	years	seconds	$3.153\,6 \times 10^{7}$
$1.141\,552\,5 \times 10^{-4}$	years	hours	8.760×10^{3}
	Torque—see *Energy*		
	Velocity		
3.280 84	feet/second	metres/second	0.304 8
$1.968\,504 \times 10^{2}$	feet/minute	metres/second	5.08×10^{-3}
3.6	kilometres/hour	metres/second	0.277 778
$3.728\,227 \times 10^{-2}$	miles/minute	metres/second	$2.682\,240 \times 10$
2.236 94	miles/hour	metres/second	0.447 04
1.942 60	UK knots	metres/second	0.514 773
1.943 85	International knots	metres/second	0.514 444
$1.1\dot{3}\dot{6} \times 10^{-2}$	UK miles/minute	feet/second	8.8×10
	*Viscosity—dynamic**		
10	poise	newton seconds/square metre	10^{-1}
$1.019\,72 \times 10^{-1}$	kilogram force seconds/square metre	newton seconds/square metre	9.806 65
$6.719\,71 \times 10^{-1}$	poundal seconds/square foot	newton seconds/square metre	1.488 16
$2.088\,542 \times 10^{-2}$	pound force seconds/square foot	newton seconds/square metre	$4.788\,03 \times 10$
	Viscosity—kinematic		
10^{4}	stokes	square metres/second	10^{-4}
$1.550\,03 \times 10^{3}$	square inches/second	square metres/second	$6.451\,6 \times 10^{-4}$
$1.076\,392 \times 10$	square feet/second	square metres/second	$9.290\,3 \times 10^{-2}$
$5.580\,011 \times 10^{6}$	square inches/hour	square metres/second	$1.792\,111 \times 10^{-7}$
$3.875\,009 \times 10^{4}$	square feet/hour	square metres/second	$2.580\,640 \times 10^{-5}$
3.6×10^{3}	square metres/hour	square metres/second	$2.7\dot{7} \times 10^{-4}$
	Volume		
$6.102\,37 \times 10^{4}$	cubic inches	cubic metres	$1.638\,71 \times 10^{-5}$
$3.531\,473 \times 10$	cubic feet	cubic metres	$2.831\,68 \times 10^{-2}$
1.307 95	cubic yards	cubic metres	$7.645\,55 \times 10^{-1}$
10^{3}	litres	cubic metres	10^{-3}
$2.199\,69 \times 10^{2}$	gallons (UK)	cubic metres	$4.546\,09 \times 10^{-3}$
$2.641\,72 \times 10^{2}$	gallons (US)	cubic metres	$3.785\,41 \times 10^{-3}$
$1.759\,755 \times 10^{-3}$	pints (UK)	cubic centimetres	$5.682\,61 \times 10^{2}$
$2.199\,69 \times 10^{-1}$	gallons (UK)	litres	4.546 09
$3.519\,508 \times 10$	fluid ounces (UK)	litres	$2.841\,306 \times 10^{-2}$
	Work—see *Energy*		

* newton seconds/square metre (N s/m^2)≡pascal seconds (Pa s).

Table 2.6 COMMONLY REQUIRED CONVERSIONS

Acceleration	$g = 32$ feet/second squared	=	9.806 65 metres/second squared	$m\,s^{-2}$
Angle	1 radian	=	57.295 8 degrees	°
Area	1 acre	=	4 046.86 square metres	m^2
	1 hectare	=	10 000 square metres	m^2
Density	1 gram/cubic centimetre	=	1 000 kilograms/cubic metre	$kg\,m^{-3}$
Energy	1 calorie (IC)	=	4.186 8 joules	J
	1 kilowatt hour	=	3.6 megajoules	MJ
	1 British thermal unit	=	1055.06 joules	J
	1 erg	=	10^{-7} joules	J
	1 therm	=	105.506 megajoules	MJ
	1 horsepower hour	=	2.684 52 megajoules	MJ
Force	1 dyne	=	10^{-5} newtons	N
	1 pound force	=	4.448 22 newtons	N
	1 UK ton force	=	9964.02 newtons	N
	1 kilogram force	=	9.806 65 newtons	N
Length	1 angstrom unit (Å)	=	10^{-10} metres	m
	1 micron (μm)	=	10^{-6} metres	m
	1 micron (μm)	=	$0.039\,37 \times 10^{-3}$ inches	in
	1 thousandth of an inch	=	25.4 micrometres	μm
	1 inch	=	2.54 centimetres	cm
	1 foot	=	30.48 centimetres	cm
	1 yard	=	91.44 centimetres	cm
	1 mile	=	1.609 344 kilometres	km
Mass	1 ounce (Av)	=	28.349 5 grams	g
	1 ounce (Troy)	=	31.103 5 grams	g
	1 pound (Av)	=	453.592 grams	g
	1 hundredweight	=	50.802 3 kilograms	kg
	1 UK ton (Av)	=	1 016.05 kilograms	kg
	1 short ton (2000 lbs)	=	907.185 kilograms	kg
	1 carat (metric)	=	0.2 grams	g
Power	1 horsepower	=	745.7 watts	W
Stress	1 pound force/square inch (p.s.i.)	=	6.894 76 kilopascals	kPa
	1 UK ton force/square inch	=	15.444 3 megapascals	MPa
	1 bar	=	100 kilopascals	kPa
	1 hectobar	=	10 megapascals	MPa
	1 kilogram force/square centimetre	=	98.006 5 kilopascals	kPa
	1 kilogram force/square millimetre	=	9.806 65 megapascals	MPa
	1 torr = 1 millimetre of mercury	=	133.322 pascals	Pa
	1 atmosphere	=	101.325 kilopascals	kPa
	1 pascal	=	1 newton/square metre	$N\,m^{-2}$
Surface tension	1 dyne/centimetre	=	1 millinewton/metre	$mN\,m^{-1}$
Velocity	1 foot/second	=	1.097 28 kilometres/hour	$km\,h^{-1}$
	1 mile/hour	=	1.609 344 kilometres/hour	$km\,h^{-1}$
Volume	1 cubic inch	=	16.387 1 cubic centimetres	cm^3
	1 cubic foot	=	28.316 8 cubic decimetres	dm^3
	1 cubic yard	=	0.764 555 cubic metres	m^3
	1 litre	=	1 cubic decimetre	dm^3
	1 litre	=	1.759 75 UK pints	pint
	1 UK gallon	=	4.546 09 cubic decimetres	dm^3
	1 UK gallon	=	0.160 544 cubic feet	ft^3

Table 2.7 CORRECTIONS TO TEMPERATURE VALUES IPTS-48 TO IMPLEMENT IPTS-68
(IPTS-68) - (IPTS-48) IN °C

t_{68}	0	−10	−20	−30	−40	−50	−60	−70	−80	−90	−100	t_{68} °C
−100	0.022	0.013	0.003	−0.006	−0.013	0.013	−0.005	0.007	0.012	(0.008 at O_2 point)		−100
−0	0.000	0.006	0.012	0.018	0.024	0.029	0.032	0.034	0.033	0.029	0.022	−0
t_{68} °C	0	10	20	30	40	50	60	70	80	90	100	t_{68} °C
0	0.000	−0.004	−0.007	−0.009	−0.010	−0.010	−0.010	−0.008	−0.006	−0.003	0.000	0
100	0.000	0.004	0.007	0.012	0.016	0.020	0.025	0.029	0.034	0.038	0.043	100
200	0.043	0.047	0.051	0.054	0.058	0.061	0.064	0.067	0.069	0.071	0.073	200
300	0.073	0.074	0.075	0.076	0.077	0.077	0.077	0.077	0.077	0.076	0.076	300
400	0.076	0.075	0.075	0.075	0.074	0.074	0.074	0.075	0.076	0.077	0.079	400
500	0.079	0.082	0.085	0.089	0.094	0.100	0.108	0.116	0.126	0.137	0.150	500
600	0.150	0.165	0.182	0.200	0.23	0.25	0.28	0.31	0.34	0.36	0.39	600
700	0.39	0.42	0.45	0.47	0.50	0.53	0.56	0.58	0.61	0.64	0.67	700
800	0.67	0.70	0.72	0.75	0.78	0.81	0.84	0.87	0.89	0.92	0.95	800
900	0.95	0.98	1.01	1.04	1.07	1.10	1.12	1.15	1.18	1.21	1.24	900
1 000	1.24	1.27	1.30	1.33	1.36	1.39	1.42	1.44	—	—	—	1 000
t_{68} °C	0	100	200	300	400	500	600	700	800	900	1 000	t_{68} °C
1 000	—	1.5	1.7	1.8	2.0	2.2	2.4	2.6	2.8	3.0	3.2	1 000
2 000	3.2	3.5	3.7	4.0	4.2	4.5	4.8	5.0	5.3	5.6	5.9	2 000
3 000	5.9	6.2	6.5	6.9	7.2	7.5	7.9	8.2	8.6	9.0	9.3	3 000

From BS 1826:1952 Amendment No. 1, 2 February 1970. Example: 1000°C according to IPTS-48 would be corrected to 1001.24°C to conform to IPTS-68.
For conversions from IPTS-68 to ITS-90 see Table 16.1.

Table 2.8 CORROSION CONVERSION FACTORS

The following conversion factors relating loss in weight and depth of penetration are useful in the assessment of corrosion.

density of metal in grams/cubic centimetre $= d$
density of metal in kilograms/cubic metre $= 10^3 d$

To convert B to A multiply by	*A*	*B*	*To convert A to B multiply by*
$10^{-3}d^{-1}$	millimetres	grams/square metre	$10^3 d$
$3.65 \times 10^{-1}d^{-1}$	millimetres/year	grams/square metre per day	$2.74d$
$8.76d^{-1}$	millimetres/year	grams/square metre per hour	$1.14 \times 10^{-1}d$
$3.937 \times 10^{-2}d^{-1}$	thousandths of an inch (mils)	grams/square metre	$2.54 \times 10d$
$1.44 \times 10d^{-1}$	mils/year	grams/square metre per day	$6.96 \times 10^{-2}d$
$3.45 \times 10^2 d^{-1}$	mils/year	grams/square metre per hour	$2.90 \times 10^{-3}d$
$1.201 \times 10d^{-1}$	mils	ounces/square foot	$8.326 \times 10^{-2}d$

Table 2.9 TEST SIEVE MESH NUMBERS CONVERTED TO NOMINAL APERTURE SIZE FROM BS 410:1969

Wire cloth test sieves were designated by the mesh count or number. This method, widely used until 1962, was laid down in previous British Standards—BS 410. Sieves are now designated by aperture size: *see* BS 410:1969, for full details.

The table gives the previously used mesh numbers with the corresponding nominal aperture sizes, the preferred average wire diameters in the test sieves and the tolerances.

			Aperture tolerances		
Mesh No.	*Nominal aperture size* mm	*Preferred average wire diameter in test sieve* mm	*Max. tolerance for size of an individual aperture* mm +	*Tolerance for average aperture size* mm ±	*Intermediate tolerance* mm +
3	5.60	1.60	0.50	0.17	0.34
3½	4.75	1.60	0.43	0.14	0.29
4	4.00	1.40	0.40	0.12	0.28
5	3.35	1.25	0.34	0.10	0.23
6	2.80	1.12	0.31	0.084	0.20
7	2.36	1.00	0.26	0.071	0.17
8	2.00	0.90	0.24	0.060	0.16
10	1.70	0.80	0.20	0.051	0.14
12	1.40	0.71	0.18	0.042	0.11
14	1.18	0.63	0.17	0.035	0.11
16	1.00	0.56	0.15	0.030	0.09
	µm	µm	µm +	µm ±	µm +
18	850	500	128	30	79
22	710	450	114	28	71
25	600	400	102	24	66
30	500	315	90	20	55
36	425	280	81	17	51
44	355	224	71	14	43
52	300	200	64	15	40
60	250	160	58	13	36
72	212	140	53	12	33

Table 2.9 TEST SIEVE MESH NUMBERS *continued*

Mesh No.	*Nominal aperture size* μm	*Preferred average wire diameter in test sieve* μm	*Aperture tolerances*		
			Max. tolerance for size of an individual aperture μm +	*Tolerance for average aperture size* μm ±	*Intermediate tolerance* μm +
85	180	125	51	11	31
100	150	100	48	9.4	29
120	125	90	46	8.1	27
150	106	71	43	7.4	25
170	90	63	43	6.6	25
200	75	50	41	6.1	24
240	63	45	41	5.3	23
300	53	36	38	4.8	21
350	45	32	38	4.8	21
400	38	30	36	4.0	20

Notes:

(1) No aperture size shall exceed the nominal by more than the maximum tolerance.
(2) The average aperture size shall not be greater or smaller than the nominal by more than the average tolerance size.
(3) Not more than 6% of the apertures shall be above the nominal size by more than the intermediate tolerance.

For perforated plate sieve sizes with square or round holes–*see* BS 410: 1969. Other national standards for test sieves may be found for France in NF X11–501, for Germany in DIN 4188 and for USA in ASTM E11–61.

2.1.2 Temperature scale conversions

The absolute unit of temperature, symbol K, is the kelvin which is 1/273.16 of the thermodynamic temperature of the triple point of water– *see* Section 16. Practical temperature scales are Celsius (previously Centigrade) symbol °C, and Fahrenheit, symbol °F. An absolute scale based on Fahrenheit is the Rankine, symbol °R.

Where K, C, F and R, represent the same temperature on the Kelvin, Celsius, Fahrenheit and Rankine scales, conversion formulae are:

$$K = C + 273.15 \qquad C = \tfrac{5}{9}(F - 32)$$
$$F = \tfrac{9}{5}C + 32 \qquad R = F + 459.67$$

Rapid approximate conversions between Celsius and Fahrenheit scales can be obtained from Figure 2.1.

2.2 Mathematical formulae

2.2.1 Algebra

IDENTITIES

$$a^2 - b^2 = (a-b)(a+b)$$
$$a^2 + b^2 = (a - ib)(a + ib) \text{ where } i = \sqrt{(-1)}$$
$$a^3 - b^3 = (a-b)(a^2 + ab + b^2)$$
$$a^3 + b^3 = (a+b)(a^2 - ab + b^2)$$
$$a^n - b^n = (a-b)(a^{n-1} + a^{n-2}b + \ldots + b^{n-1})$$
$$a^n + b^n = (a+b)(a^{n-1} - a^{n-2}b + \ldots + b^{n-1}) \text{ when } n \text{ is odd}$$
$$(a \pm b)^2 = a^2 \pm 2ab + b^2$$
$$(a \pm b)^3 = a^3 \pm 3a^2b + 3ab^2 \pm b^3$$
$$(a+b)^n = a^n + na^{n-1}b + \frac{n(n-1)}{2!}a^{n-2}b^2 + \ldots + \frac{n(n-1)(n-2)\ldots(n-r+1)}{r!}a^{n-r}b^r + \ldots + b^n$$

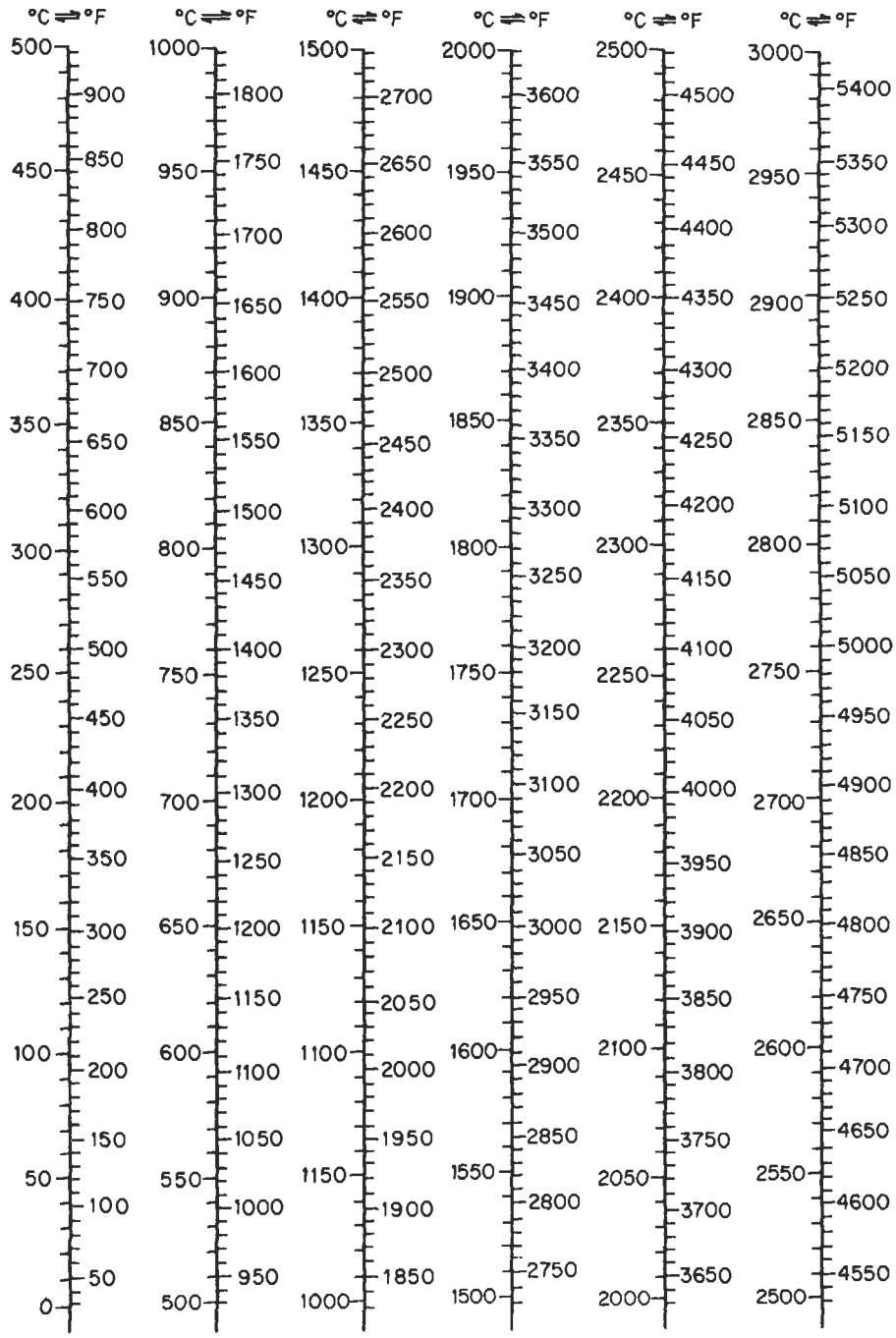


Figure 2.1 *Nomogram for approximate interconversion between Celsius and Fahrenheit temperature scales*

RATIO AND PROPORTION

If

$$\frac{a}{b}=\frac{c}{d}$$

then

$$\frac{a+b}{b}=\frac{c+d}{d}$$

and

$$\frac{a-b}{b}=\frac{c-d}{d}$$

In general,

$$\frac{a}{b}=\frac{c}{d}=\frac{e}{f}=\ldots=\left(\frac{pa^n+qc^n+re^n+\ldots}{pb^n+qd^n+rf^n+\ldots}\right)^{1/n}$$

where p, q, r and n are any quantities whatever.

LOGARITHMS

If

$$a^x=N, \text{ then } x=\log_a N$$

$$\log_a MN=\log_a M+\log_a N$$

$$\log_a\frac{M}{N}=\log_a M-\log_a N$$

$$\log_a(M^p)=p\ \log_a M$$

$$\log_a(M^{1/r})=\frac{1}{r}\log_a M$$

$$\log_b N=\frac{1}{\log_a b}\times\log_a N$$

In particular,

$$\log_e N=2.302\,585\,09\times\log_{10} N \qquad e=2.718\,28$$
$$\log_{10} N=0.434\,294\,48\times\log_e N$$
$$\log_e N\equiv\ln N \qquad \log_{10} N\equiv\lg N$$

THE QUADRATIC EQUATION

The general quadratic equation may be written

$$ax^2+bx+c=0$$

Solution $$x=\frac{-b\pm\sqrt{(b^2-4ac)}}{2a}$$

If

$$\Delta=(b^2-4ac)$$

the roots are real and equal if $\Delta=0$
the roots are imaginary and unequal if $\Delta<0$
the roots are real and unequal if $\Delta>0$

Also, if the roots are α and β,

$$\alpha+\beta=-\frac{b}{a}$$

$$\alpha\beta=\frac{c}{a}$$

THE CUBIC EQUATION

The general cubic equation may be written

$$y^3+a_1y^2+a_2y+a_3=0$$

If we put $y=x-\frac{1}{3}a_1$ the equation reduces to $x^3+ax+b=0$, where

$$a=a_2-\tfrac{1}{3}a_1^2 \quad \text{and} \quad b=\tfrac{2}{27}a_1^3-\tfrac{1}{3}a_1a_2+a_3$$

Solution $x=z+v$ or $-\dfrac{z+v}{2}\pm i\sqrt{3}\left(\dfrac{z-v}{2}\right)$,

where

$$z=\sqrt[3]{\left[-\tfrac{1}{2}b+\sqrt{\left(\frac{b^2}{4}+\frac{a^3}{27}\right)}\right]}$$

and

$$v=\sqrt[3]{\left[-\tfrac{1}{2}b-\sqrt{\left(\frac{b^2}{4}+\frac{a^3}{27}\right)}\right]}$$

Alternatively,*

$$x=2\sqrt{\left(\frac{-a}{3}\right)}\cos\frac{\theta+2k\pi}{3}\ (k=0,\ 1,\ 2)$$

where

$$\cos\theta=-\frac{b}{2}\left(\frac{-a^3}{27}\right)^{-1/2}$$

If

$$\Delta=\frac{b^2}{4}+\frac{a^3}{27}$$

there are two equal and one unequal root if $\Delta=0$
three real roots if $\Delta<0$
one real and two complex roots if $\Delta>0$

2.2.2 Series and progressions

NUMERICAL SERIES

$$1+2+3+\ldots+n=\frac{n}{2}(n+1)$$

$$1^2+2^2+3^2+\ldots+n^2=\frac{n}{6}(n+1)(2n+1)$$

*The second form of the solution is particularly useful when $\Delta<0$ (i.e. in the case of three real roots).

$$1^3+2^3+3^3+\ldots+n^3=\frac{n^2}{4}(n+1)^2$$

ARITHMETIC PROGRESSION

$$a,\ a+d,\ a+2d,\ \ldots\ a+(n-1)d$$

$$S_n=\frac{n}{2}[2a+(n-1)d]$$

where S_n denotes the sum to n terms.

GEOMETRIC PROGRESSION

$$a,\ ar,\ ar^2\ \ldots\ ar^{n-1}$$

$$S_n=\frac{a(r^n-1)}{(r-1)}=\frac{a(1-r^n)}{(1-r)}$$

where S_n denotes the sum to n terms.
If

$$r^2<1 \quad \text{and} \quad n\to\infty,\ S_\infty=\frac{a}{(1-r)}$$

TAYLOR'S SERIES

$$f(x)=f(a)+(x-a)f'(a)+\frac{(x-a)^2}{2!}f''(a)+\frac{(x-a)^3}{3!}f'''(a)+\ldots$$

MACLAURIN'S SERIES

$$f(x)=f(0)+xf'(0)+\frac{x^2}{2!}f''(0)+\frac{x^3}{3!}f'''(0)+\ldots$$

In the following series, the region of convergence is indicated in parentheses. If no region is shown, the series is convergent for all values of x.

BINOMIAL SERIES

$$(1\pm x)^n=1\pm nx+\frac{n(n-1)}{2!}x^2\pm\frac{n(n-1)(n-2)}{3!}x^3+\ldots \qquad (x^2<1)$$

$$(1\pm x)^{-n}=1\mp nx+\frac{n(n+1)}{2!}x^2\mp\frac{n(n+1)(n+2)}{3!}x^3+\ldots \qquad (x^2<1)$$

LOGARITHMIC SERIES

$$\log_e(1\pm x)=\pm x-\frac{x^2}{2}\pm\frac{x^3}{3}-\frac{x^4}{4}\pm\ldots \qquad (x^2<1)$$

$$\log_e\left(\frac{1+x}{1-x}\right)=2\left(x+\frac{x^3}{3}+\frac{x^5}{5}+\ldots\right) \qquad (x^2<1)$$

$$\log_e x=2\left[\frac{x-1}{x+1}+\frac{1}{3}\left(\frac{x-1}{x+1}\right)^3+\frac{1}{5}\left(\frac{x-1}{x+1}\right)^5+\ldots\right] \qquad (x>0)$$

$$\log_e(a+x)=\log_e a+2\left[\frac{x}{2a+x}+\frac{1}{3}\left(\frac{x}{2a+x}\right)^3+\frac{1}{5}\left(\frac{x}{2a+x}\right)^5+\ldots\right] \qquad (a>0,\ x+a>0)$$

EXPONENTIAL SERIES

$$e = 1+1+\frac{1}{2!}+\frac{1}{3!}+\frac{1}{4!}+\ldots$$

$$e^x=1+x+\frac{x^2}{2!}+\frac{x^3}{3!}+\frac{x^4}{4!}+\ldots$$

$$a^x=1+x\log_e a+\frac{(x\log_e a)^2}{2!}+\frac{(x\log_e a)^3}{3!}+\ldots$$

TRIGONOMETRIC SERIES

$$\sin x=x-\frac{x^3}{3!}+\frac{x^5}{5!}-\frac{x^7}{7!}+\ldots$$

$$\cos x=1-\frac{x^2}{2!}+\frac{x^4}{4!}-\frac{x^6}{6!}+\ldots$$

$$\tan x=x+\frac{x^3}{3}+\frac{2x^5}{15}+\frac{17x^7}{315}+\frac{62x^9}{2835}+\ldots \qquad \left(-\frac{\pi}{2}<x<\frac{\pi}{2}\right)$$

$$\sin^{-1} x=x+\frac{1}{2}\cdot\frac{x^3}{3}+\frac{1}{2}\cdot\frac{3}{4}\cdot\frac{x^5}{5}+\frac{1}{2}\cdot\frac{3}{4}\cdot\frac{5}{6}\cdot\frac{x^7}{7}+\ldots \qquad (-1\le x\le 1)$$

$$\cos^{-1} x=\frac{\pi}{2}-\sin^{-1} x$$

$$\tan^{-1} x=x-\frac{x^3}{3}+\frac{x^5}{5}-\frac{x^7}{7}+\ldots \qquad (-1\le x\le 1)$$

If

$$x=1,\ \frac{\pi}{4}=1-\frac{1}{3}+\frac{1}{5}-\frac{1}{7}+\ldots$$

$$\cot^{-1} x=\frac{\pi}{2}-\tan^{-1} x$$

SERIES FOR HYPERBOLIC FUNCTIONS

$$\sinh x=x+\frac{x^3}{3!}+\frac{x^5}{5!}+\frac{x^7}{7!}+\ldots$$

$$\cosh x=1+\frac{x^2}{2!}+\frac{x^4}{4!}+\frac{x^6}{6!}+\ldots$$

$$\tanh x=x-\frac{x^3}{3}+\frac{2x^5}{15}-\frac{17x^7}{315}+\frac{62x^9}{2835}\ldots \qquad \left(-\frac{\pi}{2}<x<\frac{\pi}{2}\right)$$

$$\sinh^{-1} x=x-\frac{1}{2}\cdot\frac{x^3}{3}+\frac{1}{2}\cdot\frac{3}{4}\cdot\frac{x^5}{5}-\frac{1}{2}\cdot\frac{3}{4}\cdot\frac{5}{6}\cdot\frac{x^7}{7}+\ldots \qquad (-1<x<1)$$

$$\tanh^{-1} x=x+\frac{x^3}{3}+\frac{x^5}{5}+\frac{x^7}{7}+\ldots \qquad (-1<x<1)$$

$$\coth^{-1} x = \frac{1}{x} + \frac{1}{3x^3} + \frac{1}{5x^5} + \frac{1}{7x^7} + \ldots \qquad (-1 < x < 1)$$

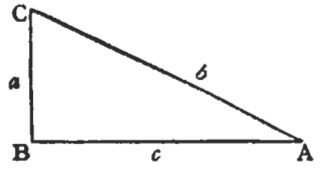
2.2.3 Trigonometry

DEFINITIONS AND SIMPLE RELATIONSHIPS

$$\sin A = \frac{a}{b}$$

$$\cos A = \frac{c}{b}$$

$$\tan A = \frac{a}{c}$$



$$\text{cosec } A = \csc A = \frac{b}{a} = \frac{1}{\sin A}; \quad \sec A = \frac{b}{c} = \frac{1}{\cos A}; \quad \cot A = \frac{c}{a} = \frac{1}{\tan A}$$

$$\text{versin } A = \text{vers } A = 1 - \cos A$$
$$\text{coversin } A = \text{covers } A = 1 - \sin A$$
$$\text{haversin } A = \text{hav } A = \tfrac{1}{2}\text{versin } A$$
$$\sin^2 A + \cos^2 A = 1$$

$$\tan A = \frac{\sin A}{\cos A}; \quad \cot A = \frac{\cos A}{\sin A}$$

$$1 + \tan^2 A = \sec^2 A$$
$$1 + \cot^2 A = \text{cosec}^2 A$$

RADIAN MEASURE

π radians $= 180°$, $\pi = 3.141\,59\ldots$

COMPOUND ANGLES

$$\sin (A + B) = \sin A \cos B + \cos A \sin B$$
$$\cos (A + B) = \cos A \cos B - \sin A \sin B$$
$$\sin (A - B) = \sin A \cos B - \cos A \sin B$$
$$\cos (A - B) = \cos A \cos B + \sin A \sin B$$

$$\tan (A + B) = \frac{\tan A + \tan B}{1 - \tan A \tan B}$$

$$\tan (A - B) = \frac{\tan A - \tan B}{1 + \tan A \tan B}$$

$$\sin 2A = 2 \sin A \cos A$$
$$\cos 2A = \cos^2 A - \sin^2 A = 1 - 2\sin^2 A = \cos^2 A - 1$$
$$\tan 2A = \frac{2 \tan A}{1 - \tan^2 A}$$
$$\sin 3A = 3 \sin A - 4 \sin^3 A$$
$$\cos 3A = 4 \cos^3 A - 3 \cos A$$

$$\left.\begin{aligned} \sin A &= \frac{2t}{1+t^2} \\ \cos A &= \frac{1-t^2}{1+t^2} \end{aligned}\right\} \text{where } t = \tan\frac{A}{2}$$

$$\sin A+\sin B=2\sin\frac{A+B}{2}\cos\frac{A-B}{2}$$

$$\sin A-\sin B=2\cos\frac{A+B}{2}\sin\frac{A-B}{2}$$

$$\cos A+\cos B=2\cos\frac{A+B}{2}\cos\frac{A-B}{2}$$

$$\cos B-\cos A=2\sin\frac{A+B}{2}\sin\frac{A-B}{2}$$

Table 2.10 SIGN AND VALUE OF THE FUNCTIONS BETWEEN 0° AND 360°

Degrees	0°		90°		180°		270°		360°	30°	45°	60°
Quadrant		1		2		3		4				
sin	0	+	1	+	0	−	−1	−	0	1/2	$1/\sqrt{2}$	$\sqrt{3}/2$
cos	1	+	0	−	−1	−	0	+	1	$\sqrt{3}/2$	$1/\sqrt{2}$	1/2
tan	0	+	∞	−	0	+	∞	−	0	$1/\sqrt{3}$	1	$\sqrt{3}$
cot	∞	+	0	−	∞	+	0	−	∞	$\sqrt{3}$	1	$1/\sqrt{3}$

Table 2.11 SUPPLEMENTARY AND COMPLEMENTARY ANGLES

$x=$	$90\pm\alpha$	$180\pm\alpha$	$270\pm\alpha$	$n360\pm\alpha$(or $\pm\alpha$)
sin x	$\pm\cos\alpha$	$\mp\sin\alpha$	$-\cos\alpha$	$\pm\sin\alpha$
cos x	$\mp\sin\alpha$	$-\cos\alpha$	$\pm\sin\alpha$	$+\cos\alpha$
tan x	$\mp\cot\alpha$	$\pm\tan\alpha$	$\mp\cot\alpha$	$\pm\tan\alpha$
cot x	$\mp\tan\alpha$	$\pm\cot\alpha$	$\mp\tan\alpha$	$\pm\cot\alpha$

PROPERTIES OF TRIANGLES

$$\frac{a}{\sin A}=\frac{b}{\sin B}=\frac{c}{\sin C}=2R, \text{ where } R=\text{radius of circumcircle}$$

$$a^2=b^2+c^2-2bc\cos A$$

$$\tan\frac{B-C}{2}=\frac{b-c}{b+c}\cot\frac{A}{2}$$

$$a=b\cos C+c\cos B$$

Area of triangle $=\triangle=\frac{1}{2}ab\sin C=\sqrt{[s(s-a)(s-b)(s-c)]}$, where $s=\frac{1}{2}(a+b+c)$

$$\sin\frac{A}{2}=\sqrt{\left[\frac{(s-b)(s-c)}{bc}\right]}$$

$$\cos\frac{A}{2}=\sqrt{\left[\frac{s(s-a)}{bc}\right]}$$

$$\tan\frac{A}{2}=\sqrt{\left[\frac{(s-b)(s-c)}{s(s-a)}\right]}$$

$$A+B+C=180°$$

$$\sin A+\sin B+\sin C=4\cos\frac{A}{2}\cos\frac{B}{2}\cos\frac{C}{2}$$

$$\cos A+\cos B+\cos C = 4\sin\frac{A}{2}\sin\frac{B}{2}\sin\frac{C}{2}+1$$

$$\tan A+\tan B+\tan C = \tan A\tan B\tan C$$

$$\cot\frac{A}{2}+\cot\frac{B}{2}+\cot\frac{C}{2} = \cot\frac{A}{2}\cot\frac{B}{2}\cot\frac{C}{2}$$

HYPERBOLIC FUNCTIONS

$$\sinh x=\tfrac{1}{2}(e^x-e^{-x})$$

$$\cosh x=\tfrac{1}{2}(e^x+e^{-x})$$

$$\tanh x=\frac{\sinh x}{\cosh x}=\frac{e^x-e^{-x}}{e^x+e^{-x}}$$

$$\operatorname{sech} x=\frac{1}{\cosh x}=\frac{2}{e^x+e^{-x}}$$

$$\operatorname{cosech} x=\frac{1}{\sinh x}=\frac{2}{e^x-e^{-x}}$$

$$\cosh^2 x-\sinh^2 x=1$$

$$\sinh(-x)=-\sinh x$$

$$\cosh(-x)=\cosh x$$

$$\tanh(-x)=-\tanh x$$

$$\sinh(x+y)=\sinh x\cosh y+\cosh x\sinh y$$

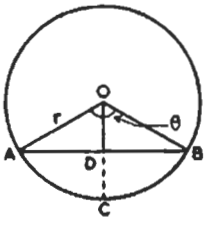
$$\cosh(x+y)=\cosh x\cosh y+\sinh x\sinh y$$

(*See also* 'Series and progressions'.)

2.2.4 Mensuration

PLANE FIGURES

Parallelogram. Area = base × altitude
Triangle. Area = $\frac{1}{2}$ × base × altitude
Trapezium. Area = $\frac{1}{2}$(sum of parallel sides) × altitude
Circle. Radius = r



$\theta = A\hat{O}B$ (*measured in radians*) $OD = x$

Area = πr^2; circumference = $2\pi r$
Length of arc ACB = $r\theta$
Area of sector OACB = $\frac{1}{2}r^2\theta$

$$\text{Length of chord AB} = 2r\sin\frac{\theta}{2}$$

$$\text{Area of segment ACB} = \tfrac{1}{2}r^2(\theta-\sin\theta)=\frac{\pi r^2}{2}-\left[x\sqrt{(r^2-x^2)}+r^2\sin^{-1}\left(\frac{x}{r}\right)\right]$$

Ellipse. Area $=\pi ab$, where a and b are the semi-axes

$$\text{Perimeter} = 2\pi\sqrt{\left(\frac{a^2+b^2}{2}\right)} \text{ (approximate)}$$

SOLID FIGURES

Rectangular prism. Sides a, b and c
Surface area $= 2(ab+bc+ca)$
Volume $= abc$
Diagonal $= \sqrt{(a^2+b^2+c^2)}$

Sphere. Radius $= r$
Surface area $= 4\pi r^2$; volume $= \frac{4}{3}\pi r^3$
Curved area of spherical segment, height $h = 2\pi rh$
Volume of spherical segment, height $h = \frac{1}{3}\pi h^2(3r-h)$
Curved area of spherical zone between two parallel planes, distance l apart $= 2\pi rl$

Spherical shell. Internal radius $= r$, external radius $= R$
Volume of shell $= \frac{4}{3}\pi(R^3-r^3)$

$$= \tfrac{4}{3}\pi t^3 + 4\pi trR$$

$$= 4\pi r'^2 t + \frac{\pi}{3}t^3$$

where t = thickness $= R-r$
and r' = mean radius $= \frac{1}{2}(R+r)$

*Right circular cylinder.** Height $= h$, radius $= r$
Area of curved surface $= 2\pi rh$
Total surface area $= 2\pi r(h+r)$
Volume $= \pi r^2 h$

Right circular cone.† Radius of base $= r$, height $= h$
Area of curved surface $= \pi r\sqrt{(r^2+h^2)}$

$$\text{Volume} = \frac{\pi}{3}r^2h$$

Area of curved surface of frustrum (radii R and r) $= \pi(R+r)\sqrt{[h^2+(R-r)^2]}$

$$\text{Volume of frustrum (radii } R \text{ and } r) = \frac{\pi h}{3}(R^2+Rr+r^2)$$

2.2.5 Co-ordinate geometry (two dimensions, rectangular axes)

The length d of the straight line joining the points $A(x_1, y_1)$ and $B(x_2, y_2)$ is given by

$$d = \pm\sqrt{[(x_2-x_1)^2+(y_2-y_1)^2]}$$

If $P(x, y)$ is a point on AB such that $\frac{AP}{PB} = \frac{m}{n}$,

$$x = \frac{mx_2+nx_1}{m+n};\quad y = \frac{my_2+ny_1}{m+n}$$

STRAIGHT LINE

The general equation to a straight line is,

$$ax+by+c=0$$

* Volume of *any* cylinder = area of base × vertical height.
† Volume of *any* cone or pyramid = ⅓[area of base × perpendicular distance from vertex to base].

Slope $= -\frac{a}{b}$. Intercept on y-axis $= -\frac{c}{b}$

Alternative forms are

1. $\frac{y_2-y_1}{x_2-x_1}=\frac{y-y_1}{x-x_1}$ for the line joining the points (x_1, y_1) and (x_2, y_2)
2. $y=mx+c$ for the line of slope, m, cutting y-axis at point $(0, c)$.
3. $y-y_1=m(x-x_1)$ for the line through the point (x_1, y_1), slope m.
4. $\frac{x}{a}+\frac{y}{b}=1$ for the line making intercepts of a and b on the axes of x and y, respectively.
5. $x\cos\alpha+y\sin\alpha=p$, where p is the length of the perpendicular from the origin to the line and α is the angle between the perpendicular and the positive direction of the x-axis.

The perpendicular distance d from the point (x_1, y_1) to the line $ax+by+c=0$ is

$$d=\pm\frac{ax_1+by_1+c}{\sqrt{(a^2+b^2)}}$$

The angle θ between two lines of slopes m_1 and m_2 is given by:

$$\tan\theta=\frac{m_1-m_2}{1+m_1m_2}$$

If the two lines are parallel, $m_1=m_2$
If the two lines are perpendicular, $m_1m_2=-1$

TRIANGLE

The area of a triangle, vertices (x_1, y_1), (x_2, y_2) and (x_3, y_3) is

$$\triangle=\tfrac{1}{2}(x_1y_2-x_2y_1+x_2y_3-x_3y_2+x_3y_1-x_1y_3)$$

CIRCLE

The general equation to a circle is

$$x^2+y^2+2gx+2fy+c=0$$

centre $(-g, -f)$; radius $=\sqrt{(g^2+f^2-c)}$

Equation to tangent at the point (x_1, y_1) on the circle is

$$xx_1+yy_1+g(x+x_1)+f(y+y_1)+c=0$$

An alternative form of the equation to the circle is

$$(x-a)^2+(y-b)^2=R^2, \text{ centre } (a, b); \text{ radius}=R$$

ELLIPSE

$\frac{x^2}{a^2}+\frac{y^2}{b^2}=1$. Centre at origin and semi-axes a and b

Equation to tangent at point (x_1, y_1) is $\frac{xx_1}{a^2}+\frac{yy_1}{b^2}=1$

PARABOLA

$y^2=4ax$. Vertex at origin, *latus rectum* $=2a$

Equation to tangent at point (x_1, y_1) is $yy_1=2a(x+x_1)$

HYPERBOLA

$\frac{x^2}{a^2}-\frac{y^2}{b^2}=1$. Centre at origin and semi-axes a and b

Equation to tangent at point (x_1, y_1) is $\frac{xx_1}{a^2}-\frac{yy_1}{b^2}=1$

The asymptotes are $\frac{x}{a}\pm\frac{y}{b}=0$

2.2.6 Calculus*

DIFFERENTIALS†

$\mathrm{d}ax=a\,\mathrm{d}x$
$\mathrm{d}(u+v)=\mathrm{d}u+\mathrm{d}v$
$\mathrm{d}uv=v\,\mathrm{d}v+v\,\mathrm{d}u$
$\mathrm{d}\frac{u}{v}=\frac{v\,\mathrm{d}u-u\,\mathrm{d}v}{v^2}$
$\mathrm{d}x^n=nx^{n-1}\,\mathrm{d}x$
$\mathrm{d}x^y=yx^{y-1}\,\mathrm{d}x+x^y\log_e x\,\mathrm{d}y$

$\mathrm{d}e^x=e^x\,\mathrm{d}x$
$\mathrm{d}e^{ax}=ae^{ax}\,\mathrm{d}x$
$\mathrm{d}a^x=a^x\log_e a\,\mathrm{d}x$
$\mathrm{d}\log_e x=x^{-1}\,\mathrm{d}x$
$\mathrm{d}\log_a x=x^{-1}\log_a e\,\mathrm{d}x$
$\mathrm{d}x^x=x^x(1+\log_e x)\mathrm{d}x$

$\mathrm{d}\sin x=\cos x\,\mathrm{d}x$
$\mathrm{d}\cos x=-\sin x\,\mathrm{d}x$
$\mathrm{d}\tan x=\sec^2 x\,\mathrm{d}x$
$\mathrm{d}\cot x=-\mathrm{cosec}^2 x\,\mathrm{d}x$
$\mathrm{d}\sec x=\tan x\sec x\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{cosec}\,x=-\cot x\cdot\mathrm{cosec}\,x\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{vers}\,x=\sin x\,\mathrm{d}x$
$\mathrm{d}\sin^{-1}x=(1-x^2)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\cos^{-1}x=-(1-x^2)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\tan^{-1}x=(1+x^2)^{-1}\,\mathrm{d}x$
$\mathrm{d}\cot^{-1}x=-(1+x^2)^{-1}\,\mathrm{d}x$
$\mathrm{d}\sec^{-1}x=x^{-1}(x^2-1)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{cosec}^{-1}x=-x^{-1}(x^2-1)^{-1/2}\,\mathrm{d}x$

$\mathrm{d}\,\mathrm{vers}^{-1}x=(2x-x^2)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\sinh x=\cosh x\,\mathrm{d}x$
$\mathrm{d}\cosh x=\sinh x\,\mathrm{d}x$
$\mathrm{d}\tanh x=\mathrm{sech}^2 x\,\mathrm{d}x$
$\mathrm{d}\coth x=-\mathrm{cosech}^2 x\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{sech}\,x=-\mathrm{sech}\,x\tanh x\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{cosech}\,x=-\mathrm{cosech}\,x\coth x\,\mathrm{d}x$
$\mathrm{d}\sinh^{-1}x=(x^2+1)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\cosh^{-1}x=(x^2-1)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\tanh^{-1}x=(1-x^2)^{-1}\,\mathrm{d}x$
$\mathrm{d}\coth^{-1}x=-(x^2-1)^{-1}\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{sech}^{-1}x=-x^{-1}(1-x^2)^{-1/2}\,\mathrm{d}x$
$\mathrm{d}\,\mathrm{cosech}^{-1}x=-x^{-1}(x^2+1)^{-1/2}\,\mathrm{d}x$

INTEGRALS

Elementary forms

1. $\int a\,\mathrm{d}x=ax$
2. $\int a\cdot f(x)\,\mathrm{d}x=a\int f(x)\,\mathrm{d}x$
3. $\int\phi(y)\,\mathrm{d}x=\int\frac{\phi(y)}{y'}\mathrm{d}y,$ where $y'=\frac{\mathrm{d}y}{\mathrm{d}x}$
4. $\int(u+v)\,\mathrm{d}x=\int u\,\mathrm{d}x+\int v\,\mathrm{d}x,$ where u and v are any functions of x
5. $\int u\,\mathrm{d}v=uv-\int v\,\mathrm{d}u$

* From *Handbook of Chemistry and Physics*, Cleveland, Ohio, 1945.
† Differentials have been written as above for ease in use, e.g. $dax=adx$ instead of $(\mathrm{d}/\mathrm{d}x)ax=a$, which is the mathematically correct form.

6. $\int u\frac{dv}{dx}dx = uv - \int v\frac{dx}{dx}dx$

7. $\int x^n\,dx = \frac{x^{n+1}}{n+1}, \qquad (n \neq -1)$

8. $\int \frac{f'(x)\,dx}{f(x)} = \log f(x), \qquad [df(x) = f'(x)\,dx]$

9. $\int \frac{dx}{x} = \log x, \text{ or } \log(-x)$

10. $\int \frac{f'(x)\,dx}{2\sqrt{[f(x)]}} = \sqrt{[f(x)]} \qquad [df(x) = f'(x)\,dx]$

11. $\int e^x\,dx = e^x$

12. $\int e^{ax}\,dx = \frac{e^{ax}}{a}$

13. $\int b^{ax}\,dx = \frac{b^{ax}}{a \log b}$

14. $\int \log x\,dx = x \log x - x$

15. $\int a^x \log a\,dx = a^x$

16. $\int \frac{dx}{a^2+x^2} = \frac{1}{a}\tan^{-1}\left(\frac{x}{a}\right), \text{ or } -\frac{1}{a}\cot^{-1}\left(\frac{x}{a}\right)$

17. $\int \frac{dx}{a^2-x^2} = \frac{1}{a}\tanh^{-1}\left(\frac{x}{a}\right), \text{ or } \frac{1}{2a}\log\frac{a+x}{a-x}$

18. $\int \frac{dx}{x^2-a^2} = -\frac{1}{a}\coth^{-1}\left(\frac{x}{a}\right), \text{ or } \frac{1}{2a}\log\frac{x-a}{x+a}$

19. $\int \frac{dx}{\sqrt{(a^2-x^2)}} = \sin^{-1}\left(\frac{x}{a}\right), \text{ or } -\cos^{-1}\left(\frac{x}{a}\right)$

20. $\int \frac{dx}{\sqrt{(x^2 \pm a^2)}} = \log[x + \sqrt{(x^2 \pm a^2)}]$

21. $\int \frac{dx}{x\sqrt{(x^2-a^2)}} = \frac{1}{a}\cos^{-1}\left(\frac{a}{x}\right)$

22. $\int \frac{dx}{x\sqrt{(a^2 \pm x^2)}} = -\frac{1}{a}\log\left[\frac{a+\sqrt{(a^2 \pm x^2)}}{x}\right]$

23. $\int \frac{dx}{x\sqrt{(a+bx)}} = \frac{2}{\sqrt{(-a)}}\tan^{-1}\sqrt{\left[\frac{(a+bx)}{-a}\right]}, \text{ or } \frac{-2}{\sqrt{(a)}}\tanh^{-1}\sqrt{\left[\frac{(a+bx)}{a}\right]}$

More complex integrals are to be found in *Handbook of Chemistry and Physics*, Cleveland, Ohio, 1945.

DIFFERENTIAL EQUATIONS

Equations of the first order

1. $\frac{dy}{dx} = f(x)\phi(y)$ (Variable separable type)

 Solution $\int \frac{dy}{\phi(y)} = \int f(x)\,dx + A$

2a. $\dfrac{dy}{dx}=f\left(\dfrac{y}{x}\right)$ (Homogeneous equation)

Let $v=\dfrac{y}{x}$

Solution $\displaystyle\int\frac{dv}{f(v)-v}=\log x+A$

2b. $\dfrac{dy}{dx}=\dfrac{ax+by+c}{a'x+b'y+c'}$ (Reducible to homogeneous form if $a'b-ab'\neq 0$)

Let $x=X+h$; $y=Y+k$, where h and k are the values of x and y which satisfy equations

$$\left.\begin{aligned}ax+by+c&=0\\a'x+b'y+c'&=0\end{aligned}\right\}$$

Solution obtained as in (2a) by putting $Y=vX$

3. $M\,dx+N\,dy=0$ where M and N are functions of x and y and

$$\frac{\partial M}{\partial y}=\frac{\partial N}{\partial x}$$ (Exact equation)

Here, a function $u(x, y)$ exists such that

$$du=M\,dx+N\,dy$$

Solution $u=\displaystyle\int M\,dx\,(y\text{ constant})+\int(\text{terms in }N\text{ independent of }x)\,dy=\text{constant}$

4. $\dfrac{dy}{dx}+Py=Q$ (Linear equation)

where P and Q are functions of x only (or constants).

Solution $y\,e^{\int P\,dx}=\displaystyle\int Q\,e^{\int P\,dx}dx+A$ (Integrating factor $=e^{\int P\,dx}$)

5. $\dfrac{dy}{dx}+Py=Qy^n$ (Bernouilli's equation)

where P and Q are functions of x only (or constants).

Multiplying both sides of the equation by $(1-n)y^{-n}$, and putting $z=y^{1-n}$ the equation becomes

$$\frac{dz}{dx}+(1-n)Pz=(1-n)Q$$

This equation is linear.

Solution obtained as in 4. [Integrating factor $=e^{\int(1-n)P\,dx}$]

6. $y=x\dfrac{dy}{dx}+f\left(\dfrac{dy}{dx}\right)$ (Clairaut's form)

Let $\dfrac{dy}{dx}=p$ and differentiate the equation with respect to x,

$$\frac{dp}{dx}[x+f'(p)]=0$$

Solution $\dfrac{dp}{dx}=0$ or $x+f'(p)=0$

i.e. $p = \text{constant} = A$
or $y = Ax + B$

This solution is obtained by eliminating p from this equation and the original equation. The solution contains no arbitrary constant and is known as the *singular solution.*

Equations of the second order

7. $\dfrac{d^2y}{dx^2} = f(x)$

Solution $y = \int F(x)\,dx + Ax + B$, where $F(x) = \int f(x)\,dx$

8. $\dfrac{d^2y}{dx^2} = f(y)$

Let $\dfrac{dy}{dx} = p$; $\frac{1}{2}p^2 = \int f(y)\,dy + A$

Integration of this equation of the first order may then lead to the required solution.

9.* $a\dfrac{d^2y}{dx^2} + b\dfrac{dy}{dx} + cy = 0$ (Linear equation, constant coefficients, RHS = 0)

Auxiliary equation. $am^2 + bm + c = 0$
Solution
(a) If $b^2 > 4ac$ (roots m_1 and m_2), $Ae^{m_1 x} + Be^{m_2 x}$
(b) If $b^2 = 4ac$ (two equal roots, m_1), $e^{m_1 x}(Ax + B)$
(c) If $b^2 < 4ac$ (roots $m_1 \pm im_2$), $e^{m_1 x}(A \sin m_2 x + B \cos m_2 x)$
or $Ce^{m_1 x} \sin(m_2 x + \alpha)$
or $Ce^{m_1 x} \cos(m_2 x - \alpha)$

10.* $a\dfrac{d^2y}{dx^2} + b\dfrac{dy}{dx} + cy = P$ (Linear equation, constant coefficients, RHS a function of x only)

Solution y = complementary function + particular integral.
The *complementary function* is the solution of the equation when $P = 0$ [*see* (9)].
The *particular integral* is *any* solution of the equation which involves no arbitrary constants.
The following examples of values of the particular integral may be useful:
(a) $P = \text{constant} = m$

Particular solution $y = \dfrac{m}{c}$

(b) $P = p + qx + rx^2 + \ldots$ (p, q, r ... are constants)
Particular solution $y = A + Bx + Cx^2 + \ldots$
If $C \neq 0$, P and y are of the same degree.

If $C = 0$, P and $\dfrac{dy}{dx}$ are of the same degree.

(c) $P = k\,e^{mx}$
Particular solution $y = A\,e^{mx}$
If e^{mx} is a term of the complementary function, try $y = Ax\,e^{mx}$
If $x\,e^{mx}$ is a term of the complementary function, try $y = Ax^2\,e^{mx}$.
(d) $P = l \sin nx + m \cos nx$ (l and m constants, or zero)
Particular solution $y = A \sin nx + B \cos nx$
If $C \sin nx + D \cos nx$ is a term of the complementary function try
$Ax \sin nx + Bx \cos$

Note: The constants A, B, C, D, etc. in the particular solutions are evaluated by substitution in the original equation.

* Reproduced with permission from G. W. Caunt, *Introduction to the Infinitesimal Calculus*, Oxford University Press, 1928.

3 General physical and chemical constants

Table 3.1 ATOMIC WEIGHTS AND ATOMIC NUMBERS OF THE ELEMENTS

Name	*Symbol*	*Atomic number*	*International atomic weights* 1971* $^{12}C = 12$	*Name*	*Symbol*	*Atomic number*	*International atomic weights* 1971* $^{12}C = 12$
Actinium	Ac	89	(227)	Lanthanum	La	57	138.905_5
Aluminium	Al	13	26.981 54	Lawrencium	Lr	103	(260)
Americium	Am	95	(243)	Lead	Pb	82	207.2
Antimony	Sb	51	121.7_3	Lithium	Li	3	6.94_1
Argon	Ar	18	39.94_8	Lutetium	Lu	71	174.97
Arsenic	As	33	74.921 6	Magnesium	Mg	12	24.305
Astatine	At	85	(210)	Manganese	Mn	25	54.938 0
Barium	Ba	56	137.3_4	Mendelevium	Md	101	(258)
Berkelium	Bk	97	(247)	Mercury	Hg	80	200.5_9
Beryllium	Be	4	9.012 18	Molybdenum	Mo	42	95.9_4
Bismuth	Bi	83	208.980 4	Neodymium	Nd	60	144.2_4
Boron	B	5	10.81	Neon	Ne	10	20.17_9
Bromine	Br	35	79.904	Neptunium	Np	93	237.048 2
Cadmium	Cd	48	112.40	Nickel	Ni	28	58.69
Caesium	Cs	55	132.905 4	Niobium			
Calcium	Ca	20	40.08	(Columbium)	Nb	41	92.906 4
Californium	Cf	98	(251)	Nitrogen	N	7	14.006 7
Carbon	C	6	12.011	Nobelium	No	102	(259)
Cerium	Ce	58	140.12	Osmium	Os	76	190.2
Chlorine	Cl	17	35.453	Oxygen	O	8	15.999_4
Chromium	Cr	24	51.996	Palladium	Pd	46	106.42
Cobalt	Co	27	58.933 2	Phosphorus	P	15	30.973 8
Copper	Cu	29	63.54_6	Platinum	Pt	78	195.0_9
Curium	Cm	96	(247)	Plutonium	Pu	94	(244)
Dysprosium	Dy	66	162.5_0	Polonium	Po	84	(209)
Einstenium	Es	99	(254)	Potassium	K	19	39.09_8
Erbium	Er	68	167.2_6	Praseodymium	Pr	59	140.908
Europium	Eu	63	151.96	Promethium	Pm	61	(145)
Fermium	Fm	100	(257)	Protactinium	Pa	91	231.035 9
Fluorine	F	9	18.998 40	Radium	Ra	88	226.025
Francium	Fr	87	(223)	Radon	Rn	86	(222)
Gadolinium	Gd	64	157.2_5	Rhenium	Re	75	186.2
Gallium	Ga	31	69.72	Rhodium	Rh	45	102.905 5
Germanium	Ge	32	72.5_9	Rubidium	Rb	37	85.467_8
Gold	Au	79	196.966 5	Ruthenium	Ru	44	101.0_7
Hafnium	Hf	72	178.4_9	Samarium	Sm	62	150.36
Helium	He	2	4.002 60	Scandium	Sc	21	44.955 9
Holmium	Ho	67	164.930 4	Selenium	Se	34	78.9_6
Hydrogen	H	1	1.007 9	Silicon	Si	14	28.085 5
Indium	In	49	114.82	Silver	Ag	47	107.868
Iodine	I	53	126.904 5	Sodium	Na	11	22.989 8
Iridium	Ir	77	192.2_2	Strontium	Sr	38	87.62
Iron	Fe	26	55.84_7	Sulphur	S	16	32.06
Krypton	Kr	36	83.80	Tantalum	Ta	73	180.947_9

Table 3.1 ATOMIC WEIGHTS AND ATOMIC NUMBERS OF THE ELEMENTS—*continued*

Name	*Symbol*	*Atomic number*	*International atomic weights* 1971* $^{12}C = 12$	*Name*	*Symbol*	*Atomic number*	*International atomic weights* 1971* $^{12}C = 12$
Technetium	Tc	43	(98)	Tungsten	W	74	183.8_5
Tellurium	Te	52	127.6_0	Uranium	U	92	238.029
Terbium	Tb	65	158.925	Vanadium	V	23	50.941_4
Thallium	Tl	81	204.383	Xenon	Xe	54	131.30
Thorium	Th	90	232.038	Ytterbium	Yb	70	173.0_4
Thulium	Tm	69	168.934	Yttrium	Y	39	88.9059
Tin	Sn	50	118.71	Zinc	Zn	30	65.39
Titanium	Ti	22	47.88	Zirconium	Zr	40	91.224

* Atomic Weights of the Elements 1981, *Pure and Applied Chemistry* 1983, 55 (7), 1101–1136. A value given in brackets denotes the mass number of the isotope of longest known half-life. Because of natural variation in the relative abundance of the isotopes of some elements, their atomic weights may vary. Apart from this they are considered reliable to ± 1 in the last digit, or ± 3 if that digit is subscript.

Table 3.2 GENERAL PHYSICAL CONSTANTS

The probable errors of the various quantities may be obtained from the reference given at the end of the table.

Quantity	*Symbol*	*Value*	*Units*
Acceleration due to gravity (standard)	g_n	9.806 65	$m\,s^{-2}$
Atmospheric pressure (standard)	A_0	$1.013\,25 \times 10^{5}$	Pa
Atomic mass unit	m_u	$1.660\,565\,5 \times 10^{-27}$	kg
Atomic weight of electron	$N_A m_e$	$5.486\,802\,6 \times 10^{-4}$	u*
Avogadro number	N_A	$6.022\,045 \times 10^{23}$	mol^{-1}
Boltzmann's constant	k	$1.380\,662 \times 10^{-23}$	$J\,K^{-1}$
Bohr radius	a_0	$5.291\,770\,6 \times 10^{-11}$	m
Bohr magneton	μ_B	$9.274\,078 \times 10^{-24}$	$J\,T^{-1}$
Charge in electrolysis of 1 g hydrogen	F/H	$9.572\,378 \times 10^{4}$	C
Compton wavelength of electron	λ_C	$2.426\,308\,9 \times 10^{-12}$	m
Classical electron radius	r_e	$2.817\,938\,0 \times 10^{-15}$	m
Compton wavelength of proton	$\lambda_{C,p}$	$1.321\,409\,9 \times 10^{-15}$	m
Compton wavelength of neutron	$\lambda_{C,n}$	$1.319\,590\,9 \times 10^{-15}$	m
Density of the earth (average)	δ	5.518×10^{3}	$kg\,m^{-3}$
(core)		1.072×10^{4}	$kg\,m^{-3}$
Density of mercury (0°C, A_0)	D_0	$1.359\,508 \times 10^{4}$	$kg\,m^{-3}$
Density of water (max)	$\delta_m(H_2O)$	$9.999\,72 \times 10^{2}$	$kg\,m^{-3}$
Electronic charge	e	$1.602\,189\,2 \times 10^{-19}$	C
Electron rest mass	m_e	$9.109\,534 \times 10^{-31}$	kg
Electron volt energy	E_p	$1.602\,192 \times 10^{-19}$	J
Electron magnetic moment	μ_e	$9.284\,832 \times 10^{-24}$	$J\,T^{-1}$
Faraday constant	F	$9.648\,456 \times 10^{4}$	$C\,mol^{-1}$
Fine structure constant	α	$7.297\,350\,6 \times 10^{-3}$	—
Gas constant	R_0	8.314 41	$J\,K^{-1}\,mol^{-1}$
Gravitational constant	G	$6.672\,0 \times 10^{-11}$	$Nm^2\,kg^{-2}$
Ice point (absolute value)	T_0	$2.731\,5 \times 10^{2}$	K
Litre (12th CGPM 1964)	l	1.0 exactly $\times 10^{-3}$	m^3
(1963 weights and measures)		$1.000\,028 \times 10^{-3}$	m^3
Neutron rest mass	m_n	$1.674\,954\,3 \times 10^{-27}$	kg
Planck's constant	h	$6.626\,176 \times 10^{-34}$	Js
Proton rest mass	m_p	$1.672\,648\,5 \times 10^{-27}$	kg
Radiation constant–first	$8\pi hc$	$4.992\,563 \times 10^{-24}$	Jm
Radiation constant–second	$c_2 = hc/k$	$1.438\,786 \times 10^{-2}$	mK
Rydberg's constant	R_∞	$1.097\,373\,177 \times 10^{7}$	m^{-1}
Stefan–Boltzmann constant	σ	$5.670\,32 \times 10^{-8}$	$Wm^{-2}\,K^{-4}$
Velocity of light	c	$2.997\,924\,580 \times 10^{8}$	$m\,s^{-1}$
Volume of ideal gas (0°C, A_0)	V_0	$2.241\,36 \times 10^{-2}$	$m^3\,mol^{-1}$
Wien's constant	$\lambda_m T$	$2.897\,8 \times 10^{-3}$	mK
Zeeman displacement		$4.668\,58 \times 10$	$m\,Wb^{-1}$

* u = unified atomic mass unit (amu) based on $u = \frac{1}{12}$ of the mass of ^{12}C.

REFERENCES

'Quantities, Units and Symbols', The Royal Society, 1981.

Table 3.3 MOMENTS OF INERTIA

Moment of inertia $= Mk^2$ where M is mass and k radius of gyration

Body	*Dimensions*	*Axis**	k^2
Uniform thin rod	length l	Through centre, perpendicular to rod	$l^2/12$
		Through end, perpendicular to rod	$l^2/3$
Rectangular lamina	sides a and b	Through centre, perpendicular to plane of lamina	$(a^2+b^2)/12$
		Through centre, parallel to side b	$a^2/12$
Circular lamina	radius r	Through centre, perpendicular to plane of lamina	$r^2/2$
		Through any diameter	$r^2/4$
Annular lamina	radii r_1 and r_2	Through centre perpendicular to plane of lamina	$(r_1^2+r_2^2)/2$
		Through any diameter	$(r_1^2+r_2^2)/4$
Rectangular solid	sides a, b and c	Through centre, perpendicular to face ab	$(a^2+b^2)/12$
Sphere	radius r	Through any diameter	$2r^2/5$
Spherical shell	radii r_1 and r_2	Through any diameter	$2(r_1^5-r_2^5)/5(r_1^3-r_2^3)$
Thin spherical shell	radius r	Through any diameter	$2r^2/3$
Right circular cylinder	radius r length l	Longitudinal axis through centre	$r^2/2$
		Through centre perpendicular to longitudinal axis	$r^2/4+l^2/12$
Hollow circular cylinder	radii r_1 and r_2 length l	Longitudinal axis through centre	$(r_1^2+r_2^2)/2$
		Through centre perpendicular to longitudinal axis	$(r_1^2+r_2^2)/4+l^2/12$
Thin hollow circular cylinder	radius r length l	Longitudinal axis through centre	r^2
		Through centre perpendicular to longitudinal axis	$r^2/2+l^2/12$
Right circular cone	height h base radius r	Longitudinal axis through apex	$3r^2/10$
		Through centre of gravity perpendicular to longitudinal axis	$3(r^2+h^2/4)/20$
Ellipsoid	semi-axis a, n and c	Through centre along axis a	$(b^2+c^2)/5$

* If the moment of inertia I_g about an axis through the centre of gravity is known, then the moment, I, about any other parallel axis may be obtained from

$$I = I_g + Mh^2$$

where h is the distance from the centre of gravity to the parallel axis.

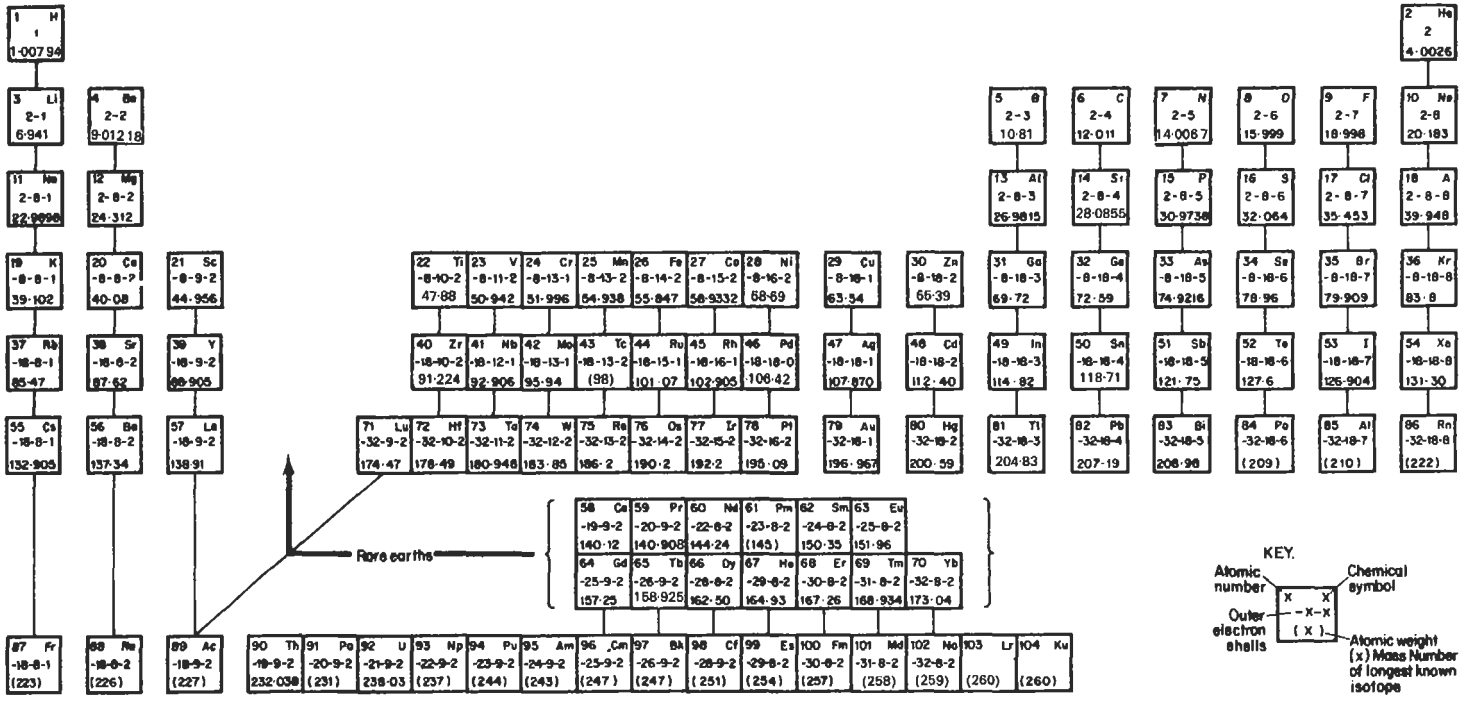


Figure 3.1 *The Periodic Table*

3.1 Radioactive isotopes and radiation sources

Tables 3.4, 3.5 and 3.6 are so arranged as to assist in selecting an isotope with a given half-life and decay radiation energy, for positron, beta and gamma emitters.

Tables 3.7 to 3.12 list the most commonly used commercially available alpha, beta and neutron sources.

Table 3.4 POSITRON EMITTERS (USEFUL NUCLIDES)

Isotope	*Half-life*	β^+ *energies* MeV %
Oxygen-15	2.0 min	1.73–99.9
Nitrogen-13	10.0 min	1.20–99.8
Bromine-80	17.4 min	0.85–2.6
Carbon-11	20.4 min	0.96–99.8
Manganese-52m	21.1 min	2.63–96.4
Gallium-68	68.0 min	0.82–1.1
		1.90–87.9
Fluorine-18	109.8 min	0.63–100
Titanium-45	3.1 h	1.04–84.8
Scandium-44	3.9 h	1.48–94.4
Iron-52	8.3 h	0.80–56.0
(Daughter: Mn-52m)		
Zinc-62	9.3 h	0.61–7.6
Gallium-66	9.4 h	0.36–1.0
		0.77–0.7
		0.92–4.1
		1.78–0.4
		4.15–49.6
Copper-64	12.7 h	0.65–17.9
Niobium-90	14.6 h	1.50–53
Cobalt-55	17.5 h	0.44–0.27
		0.48–0.03
		0.65–0.46
Arsenic-72	26.0 h	0.81–0.5
		1.87–6.0
		2.50–64.0
		2.64–0.1
		3.33–16.5
Nickel-57	36.1 h	0.30–0.41
		0.46–0.87
		0.72–5.7
		0.84–33.1
Gold-194	39.5 h	1.16–0.64
		1.49–1.0
Bromine-77	56 h	0.34–0.73
Yttrium-87	80.3 h	0.45–0.16
Iodine-124	4.2 d	0.81–0.29
		1.53–11.2
		2.14–11.2
Manganese-52	5.6 d	0.58–29.6
Caesium-132	6.5 d	0.6 –0.3
Iodine-126	13.0 d	0.47–0.2
		1.13–0.8
Vanadium-48	16.2 d	0.56–0.1
		0.70–50.0
		1.99–0.09
		0.94–25.7
Arsenic-74	17.8 d	1.54–3.4
Rubidium-84	32.8 d	0.78–14.4
		1.66–11.9
Cobalt-58	70.8 d	0.48–15.0
Cobalt-56	78.8 d	0.42–1.1
		1.46–18.8
Yttrium-88	106.6 d	0.76–0.22
Zinc-65	243.9 d	0.33–1.5
Sodium-22	2.60 yr	0.55–89.8
		1.89–0.06
Aluminium-26	7.2×10^5 yr	1.17–81.8

Table 3.5 BETA ENERGIES AND HALF-LIVES

Half-life β^-*-energy* MeV	*< 1 hour*			*1–10 hours*			*10 hours–1 day*		
0–0.3	^{101}Mo,	^{233}Th		^{31}Si, ^{127}Te, ^{177}Yb	^{105}Ru, ^{165}Dy,	^{117}Cd, ^{171}Er,	^{28}Mg, ^{188}Re	^{77}Ge,	^{130}I,
0.3–0.5	^{88}Rb, ^{233}Th	^{101}Mo,	^{116m}In,	^{56}Mn, ^{97}Nb, ^{132}I, ^{177}Yb	^{61}Co, ^{105}Ru, ^{149}Nd,	^{65}Ni, ^{117}Cd, ^{171}Er,	^{28}Mg, ^{77}Ge, ^{187}W, ^{197}Pt	^{43}K, ^{97}Zr, ^{188}Re,	^{72}Ga, ^{130}I, ^{194}Ir,
0.5–0.7	^{70}Ga, ^{101}Mo, ^{199}Pt,	^{80}Br, ^{101}Tc, ^{233}Th	^{88}Rb, ^{116m}In,	^{65}Ni, ^{105}Ru, ^{132}I,	^{75}Ge, ^{117}Cd, ^{152m}Eu,	^{97}Nb, ^{127}Te, ^{171}Er	^{64}Cu, ^{97}Zr, ^{159}Gd, ^{194}Ir,	^{72}Ga, ^{130}I, ^{187}W, ^{197}Pt	^{77}Ge, ^{142}Pr, ^{188}Re,
0.7–1.0	^{49}Ca, ^{81}Se, ^{101}Tc, ^{144}Pr, ^{233}Th	^{69}Zn, ^{88}Rb, ^{116m}In, ^{155}Sm,	^{80}Br, ^{101}Mo, ^{117}In, ^{199}Pt,	^{41}Ar, ^{85m}Kr, ^{117}Cd, ^{152m}Eu,	^{56}Mn, ^{97}Nb, ^{132}I, ^{165}Dy,	^{75}Ge, ^{105}Ru, ^{139}Ba, ^{171}Er	^{28}Mg, ^{77}Ge, ^{159}Gd, ^{197}Pt	^{43}K, ^{97}Zr, ^{187}W,	^{72}Ga, ^{130}I, ^{194}Ir,
1.0–1.5	^{38}Cl, ^{80}Br, ^{101}Tc, ^{117}In, ^{155}Sm,	^{49}Ca, ^{81}Se, ^{108}Ag, ^{123m}Sn, ^{199}Pt,	^{52}V, ^{101}Mo, ^{116m}In, ^{128}I, ^{233}Th	^{31}Si, ^{61}Co, ^{97}Nb, ^{132}I, ^{171}Er,	^{41}Ar, ^{65}Ni, ^{105}Ru, ^{149}Nd, ^{176m}Lu,	^{56}Mn, ^{75}Ge, ^{117}Cd, ^{165}Dy, ^{177}Yb	^{24}Na, ^{77}Ge, ^{130}I, ^{194}Ir	^{43}K, ^{97}Zr, ^{187}W,	^{72}Ga, ^{109}Pd, ^{188}Re,
1.5–2.0	^{27}Mg, ^{66}Cu, ^{81}Se, ^{128}I,	^{49}Ca, ^{70}Ga, ^{101}Mo, ^{155}Sm,	^{51}Ti, ^{80}Br, ^{108}Ag, ^{199}Pt	^{105}Ru, ^{149}Nd,	^{117}Cd, ^{152m}Eu	^{132}I,	^{42}K, ^{77}Ge, ^{188}Re,	^{43}K, ^{97}Zr, ^{194}Ir	^{72}Ga, ^{130}I,
2.0–3.0	^{28}Al, ^{49}Sc, ^{66}Cu, ^{128}I,	^{38}Cl, ^{51}Ti, ^{88}Rb, ^{144}Pr	^{49}Ca, ^{52}V, ^{101}Mo,	^{41}Ar, ^{117}Cd,	^{56}Mn, ^{132}I,	^{65}Ni, ^{139}Ba,	^{28}Mg/^{28}Al, ^{77}Ge, ^{194}Ir	^{142}Pr,	^{72}Ga, ^{188}Re,
>3.0	^{38}Cl,	^{88}Rb					^{42}K,	^{72}Ga	

1–10 days	*10–100 days*	*100 days–1 year*	*> 1 year*
^{67}Cu, ^{76}As, ^{77}As, ^{82}Br, ^{99}Mo, ^{105}Rh, ^{131}I, ^{132}Te, ^{133}Xe, ^{143}Ce, ^{149}Pm, ^{151}Pm, ^{166}Ho, ^{169}Er, ^{175}Yb, ^{177}Lu, ^{198}Au, ^{199}Au, ^{222}Rn + D.P.	^{33}P, ^{35}S, ^{59}Fe, ^{95}Nb, ^{103}Ru, ^{115m}Cd, ^{124}Sb, $^{129m/129}$Te, ^{147}Nd, ^{160}Tb, ^{191}Os, ^{192}Ir, ^{203}Hg, ^{233}Pa	^{45}Ca, ^{110m}Ag, ^{144}Ce, ^{182}Ta	^{3}H, ^{14}C, ^{63}Ni, ^{85}Kr, ^{93}Zr, ^{106}Ru, ^{125}Sb, ^{129}I, ^{134}Cs, ^{147}Pm, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{210}Pb, ^{227}Ac, ^{228}Ra, ^{228}Th + D.P., ^{235}U + D.P., ^{238}U/^{234}Th
^{47}Sc, ^{67}Cu, ^{76}As, ^{77}As, ^{82}Br, ^{99}Mo, ^{121}Sn, ^{131}I, ^{133}Xe, ^{151}Pm, ^{161}Tb, ^{166}Ho, ^{169}Er, ^{175}Yb, ^{177}Lu, ^{199}Au, ^{222}Rn + D.P.	^{46}Sc, ^{59}Fe, ^{91}Y, ^{95}Zr, ^{103}Ru, ^{115m}Cd, ^{124}Sb, ^{126}I, $^{129m/129}$Te, ^{140}Ba, ^{141}Ce, ^{147}Nd, ^{160}Tb, ^{181}Hf, ^{185}W	^{110m}Ag, ^{123}Sn, ^{144}Ce, ^{182}Ta	^{60}Co, ^{87}Rb, ^{99}Tc, ^{125}Sb, ^{134}Cs, ^{152}Eu, ^{154}Eu, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra + D.P., ^{228}Th + D.P., ^{235}U + D.P.
^{47}Ca, ^{47}Sc, ^{67}Cu, ^{76}As, ^{77}As, ^{105}Rh, ^{111}Ag, ^{115}Cd, ^{131}I, ^{143}Ce, ^{151}Pm, ^{153}Sm, ^{161}Tb, ^{193}Os, ^{222}Rn + D.P.	^{86}Rb, $^{114m/114}$In, ^{115m}Cd, ^{124}Sb, $^{129m/129}$Te, ^{140}Ba, ^{141}Ce, ^{160}Tb, ^{192}Ir, ^{233}Pa	^{110m}Ag, ^{182}Ta	^{85}Kr, ^{90}Sr, ^{94}Nb, ^{125}Sb, ^{134}Cs, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{226}Ra + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P.
^{99}Mo, ^{111}Ag, ^{115}Cd, ^{122}Sb, ^{131}I, ^{143}Ce, ^{149}Pm, ^{151}Pm, ^{153}Sm, ^{186}Re, ^{193}Os, ^{198}Au, ^{222}Rn + D.P.	^{74}As, ^{84}Rb, ^{95}Zr, ^{103}Ru, ^{124}Sb, ^{126}I, $^{129m/129}$Te, ^{140}Ba, ^{143}Pr, ^{147}Nd, ^{160}Tb, ^{192}Ir	^{127m}Te, ^{144}Ce/^{144}Pr, ^{170}Tm	^{36}Cl, ^{152}Eu, ^{154}Eu, ^{204}Tl, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P.
^{47}Ca, ^{76}As, ^{99}Mo, ^{111}Ag, ^{115}Cd, ^{122}Sb, ^{140}La, ^{143}Ce, ^{149}Pm, ^{151}Pm, ^{186}Re, ^{193}Os, ^{210}Bi, ^{222}Rn + D.P.	^{74}As, ^{89}Sr, ^{95}Zr, ^{126}I, $^{129m/129}$Te, ^{140}Ba/^{140}La	^{123}Sn, ^{182}Ta	^{40}K, ^{137}Cs, ^{152}Eu, ^{154}Eu, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{238}U/^{234m}Pa
^{47}Ca, ^{76}As, ^{122}Sb, ^{140}La, ^{166}Ho, ^{222}Rn + D.P.	^{32}P, ^{59}Fe, ^{86}Rb, ^{91}Y, $^{114m/114}$In, ^{115m}Cd, ^{124}Sb, $^{129m/129}$Te, ^{140}Ba/^{140}La, ^{160}Tb	^{182}Ta	^{60}Co, ^{106}Ru/^{106}Rh, ^{154}Eu, ^{226}Ra + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P.
^{76}As, ^{90}Y, ^{140}La, ^{222}Rn + D.P.	^{124}Sb, ^{140}Ba/^{140}La	$^{110m/110}$Ag, ^{144}Ce/^{144}Pr	^{90}Sr/^{90}Y, ^{106}Ru/^{106}Rh, ^{226}Ra + D.P., ^{228}Th + D.P., ^{228}Ra/^{228}Ac, ^{238}U/^{234m}Pa
^{222}Rn + D.P.			^{106}Ru/^{106}Rh, ^{226}Ra + D.P.

Table 3.6 GAMMA ENERGIES AND HALF-LIVES ^{117}In,

Half-life / *γ-energy* MeV	*< 1 hour*			*1–10 hours*			*10 hours–1 day*		
0–0.3	^{27}Mg, ^{81}Se, ^{101}Tc, ^{155}Sm,	^{70}Ga, ^{94m}Nb, ^{116m}In, ^{199}Pt	^{81m}Se, ^{101}Mo, ^{117}In	^{52}Fe, ^{80m}Br, ^{105}Ru, ^{132}I, ^{149}Nd, ^{171}Er,	^{61}Co, ^{85m}Kr, ^{117}Cd, ^{134m}Cs, ^{152m}Eu, ^{177}Yb,	^{75}Ge, ^{99m}Tc, ^{127}Te, ^{139}Ba, ^{165}Dy, ^{180m}Hf	^{28}Mg, ^{77}Ge, ^{123}I, ^{194}Ir,	^{43}K, ^{97}Zr, ^{159}Gd, ^{197m}Hg,	^{55}Co, ^{109}Pd, ^{187}W, ^{197}Pt
0.3–0.5	^{51}Ti, ^{116m}In, ^{199}Pt	^{101}Mo, ^{128}I,	^{101}Tc, ^{155}Sm,	^{65}Ni, ^{87m}Sr, ^{117}Cd, ^{149}Nd, ^{171}Er,	^{75}Ge, ^{97}Nb, ^{127}Te, ^{152m}Eu,	^{85m}Kr, ^{105}Ru, ^{132}I, ^{165}Dy, ^{180m}Hf	^{28}Mg, ^{55}Co, ^{97}Zr, ^{130}I, ^{194}Ir	^{42}K, ^{69m}Zn, ^{109}Pd, ^{159}Gd,	^{43}K, ^{77}Ge, ^{123}I, ^{187}W,
0.5–0.7	^{11}C, ^{51}Ti, ^{101}Mo, ^{108}Ag, ^{144}Pr,	^{13}N, ^{80}Br, ^{101}Tc, ^{117}In, ^{155}Sm,	^{15}O, ^{81}Se, ^{104}Rh, ^{128}I, ^{199}Pt	^{18}F, ^{52}Fe, ^{68}Ga, ^{105}Ru, ^{149}Nd, ^{171}Er,	^{44}Sc, ^{65}Ni, ^{75}Ge, ^{117}Cd, ^{152m}Eu, ^{180m}Hf	^{45}Ti, ^{66}Ga, ^{97}Nb, ^{132}I, ^{165}Dy,	^{43}K, ^{72}Ga, ^{109}Pd, ^{142}Pr, ^{194}Ir	^{55}Co, ^{77}Ge, ^{123}I, ^{159}Gd,	^{64}Cu, ^{97}Zr, ^{130}I, ^{187}W,
	(Including isotopes giving 0.51 MeV gamma rays from annihilation of positrons)								
0.7–1.0	^{27}Mg, ^{80}Br, ^{101}Mo, ^{128}I,	^{51}Ti, ^{81}Se, ^{108}Ag, ^{155}Sm,	^{66}Cu, ^{88}Rb, ^{116m}In, ^{199}Pt	^{45}Ti, ^{65}Ni, ^{117}Cd, ^{152m}Eu, ^{177}Yb	^{56}Mn, ^{66}Ga, ^{132}I, ^{165}Dy,	^{61}Co, ^{105}Ru, ^{149}Nd, ^{171}Er,	^{28}Mg, ^{55}Co, $^{97}Zr/^{97m}Nb$, ^{123}I, ^{194}Ir	^{42}K, ^{72}Ga, ^{130}I,	^{43}K, ^{77}Ge, ^{109}Pd, ^{187}W,
1.0–1.5	^{27}Mg, ^{66}Cu, ^{88}Rb, ^{116m}In, ^{155}Sm,	^{49}Ca, ^{70}Ga, ^{101}Mo, ^{128}I, ^{199}Pt	^{52}V, ^{80}Br, ^{108}Ag, ^{144}Pr,	^{31}Si, ^{45}Ti, ^{68}Ga, ^{117}Cd, ^{149}Nd, ^{177}Yb	^{41}Ar, ^{65}Ni, ^{97}Nb, ^{132}I, ^{152m}Eu,	^{44}Sc, ^{66}Ga, ^{105}Ru, ^{139}Ba, ^{165}Dy,	^{24}Na, ^{55}Co, ^{77}Ge, ^{194}Ir	^{28}Mg, ^{64}Cu, ^{97}Zr,	^{43}K, ^{72}Ga, ^{130}I,
1.5–2.0	^{28}Al, ^{88}Rb,	^{38}C, ^{101}Mo,	^{52}V, ^{116m}In	^{41}Ar, ^{66}Ga, ^{105}Ru, ^{139}Ba	^{56}Mn, ^{68}Ga, ^{117}Cd,	^{65}Ni, ^{97}Nb, ^{132}I,	$^{28}Mg/^{28}Al$, ^{72}Ga, ^{142}Pr,	^{77}Ge, ^{194}Ir	^{42}K, ^{97}Zr,
2.0–3.0	^{38}Cl, ^{101}Mo,	^{49}Ca, ^{116m}In,	^{88}Rb, ^{144}Pr	^{44}Sc, ^{117}Cd,	^{56}Mn, ^{132}I	^{66}Ga,	^{24}Na, ^{72}Ga,	^{42}K, ^{77}Ge,	^{55}Co, ^{194}Ir
>3.0	^{49}Ca,	^{88}Rb		^{56}Mn,	^{66}Ga				

1–10 days	*10–100 days*	*100 days–1 year*	*> 1 year*
^{47}Sc, ^{67}Cu, ^{67}Ga, ^{77}As, ^{77}Br, ^{82}Br, ^{97}Ru, ^{99}Mo, ^{105}Rh, ^{111}Ag, ^{111}In, ^{115}Co, ^{131}I, ^{132}Te, ^{133m}Ba, ^{133m}Xe, ^{133}Xe, ^{140}La, ^{143}Ce, ^{149}Pm, ^{151}Pm, ^{153}Sm, ^{161}Tb, ^{166}Ho, ^{174}Yb, ^{177}Lu, ^{186}Re, ^{193}Os, ^{197}Hg, ^{199}Au, ^{200}Bi, ^{222}Rn + D.P., ^{224}Ra, ^{225}Ac	^{59}Fe, ^{73}As, ^{83}Rb, ^{103}Pd/^{103m}Rh, ^{103}Ru/^{103m}Rh, ^{105}Ag, ^{114m}In, ^{125}I, $^{129m/129}$Te, ^{131}Ba, ^{131m}Xe, ^{140}Ba, ^{141}Ce, ^{147}Nd, ^{160}Tb, ^{169}Yb, ^{175}Hf, ^{181}Hf, ^{183}Re, ^{185}Os, ^{191}Os, ^{192}Ir, ^{203}Hg, ^{223}Ra, ^{233}Pa	^{57}Co, ^{75}Se, ^{110m}Ag, ^{113}Sn, ^{119m}Sn, ^{127m}Te, ^{139}Ce, ^{144}Ce, ^{153}Gd, ^{170}Tm, ^{181}W, ^{182}Ta, ^{195}Au	^{44}Ti, ^{109}Cd, ^{125}Sb, ^{129}I, ^{133}Ba, ^{152}Eu, ^{154}Eu, ^{155}Eu, ^{208}Po, ^{210}Pb, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{230}Th, ^{231}Pa, ^{232}U, ^{233}U, ^{235}U + D.P., ^{237}Np, ^{238}U/^{234}Th, ^{239}Pu, ^{241}Am
^{47}Ca, ^{67}Cu, ^{67}Ga, ^{77}Br, ^{87}Y, ^{97}Ru, ^{99}Mo, ^{105}Rh, ^{111}Ag, ^{115}Cd, ^{131}I, ^{132}Cs, ^{140}La, ^{143}Ce, ^{151}Pm, ^{153}Sm, ^{161}Tb, ^{175}Yb, ^{177}Lu, ^{193}Os, ^{198}Au, ^{206}Bi, ^{222}Rn + D.P., ^{224}Ra, ^{225}Ac	^{7}Be, ^{51}Cr, ^{85}Sr, ^{103}Pd, ^{103}Ru, ^{105}Ag, ^{115m}Cd, ^{124}Sb, ^{126}I, ^{129m}Te/^{129}Te, ^{131}Ba, ^{140}Ba/^{140}La, ^{147}Nd, ^{160}Tb, ^{169}Yb, ^{175}Hf, ^{181}Hf, ^{183}Re, ^{192}Ir, ^{223}Ra, ^{233}Pa	^{75}Se, ^{106}Ru/^{106}Rh, ^{110m}Ag, ^{113}Sn/^{113m}In	^{125}Sb, ^{133}Ba, ^{134}Cs, ^{152}Eu, ^{154}Eu, ^{207}Bi, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{231}Pa, ^{232}U, ^{233}U, ^{235}U + D.P., ^{239}Pu
^{52}Mn, ^{72}As, ^{76}As, ^{77}As, ^{77}Br, ^{82}Br, ^{87}Y, ^{97}Ru, ^{99}Mo, ^{111}Ag, ^{115}Cd, ^{122}Sb, ^{124}I, ^{131}I, ^{132}Cs, ^{143}Ce, ^{149}Pm, ^{151}Pm, ^{153}Sm, ^{161}Tb, ^{166}Ha, ^{186}Re, ^{193}Os, ^{198}Au, ^{206}Bi, ^{222}Rn + D.P., ^{224}Ra, ^{225}Ac	^{48}V, ^{56}Co, ^{58}Co, ^{74}As, ^{83}Rb, ^{84}Rb, ^{85}Sr, ^{103}Ru, ^{105}Ag, ^{114m}In, ^{124}Sb, ^{126}I, ^{129m}Te/^{129}Te, ^{131}Ba, ^{140}Ba, ^{147}Nd, ^{160}Tb, ^{181}Hf, ^{185}Os, ^{192}Ir, ^{223}Ra	^{57}Co, ^{65}Zn, ^{88}Y, ^{106}Ru/^{106}Rh, ^{110m}Ag, ^{127m}Te, ^{144}Ce/^{144}Pr	^{22}Na, ^{26}Al, ^{85}Kr, ^{94}Nb, ^{125}Sb, ^{134}Cs, ^{137}Cs/^{137m}Ba, ^{152}Eu, ^{154}Eu, ^{207}Bi, ^{208}Po, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{238}U/^{234m}Pa
^{47}Ca, ^{52}Mn, ^{67}Ga, ^{72}As, ^{76}As, ^{77}Br, ^{82}Br, ^{97}Ru, ^{99}Mo, ^{111}Ag, ^{124}I, ^{131}I, ^{140}La, ^{143}Ce, ^{149}Pm, ^{151}Pm, ^{166}Ho, ^{186}Re, ^{193}Os, ^{206}Bi, ^{222}Rb + D.P.	^{46}Sc, ^{48}V, ^{56}Co, ^{58}Co, ^{83}Rb, ^{84}Rb, ^{89}Sr, ^{95}Nb, ^{95}Zr, ^{105}Ag, ^{114m}In, ^{115m}Cd, ^{124}Sb, ^{126}I, ^{129m}Te/^{129}Te, ^{131}Ba, ^{140}Ba/^{140}La, ^{160}Tb, ^{185}Os, ^{192}Ir	^{54}Mn, ^{88}Y, ^{106}Ru/^{106}Rh, ^{110m}Ag, ^{182}Ta, ^{210}Po	^{94}Nb, ^{134}Cs, ^{152}Eu, ^{154}Eu, ^{207}Bi, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{238}U/^{234m}Pa
^{47}Ca, ^{52}Mn, ^{72}As, ^{76}As, ^{77}Br, ^{82}Br, ^{122}Sb, ^{124}I, ^{132}Cs, ^{143}Ce, ^{166}Ho, ^{198}Au, ^{206}Bi, ^{222}Rn + D.P.	^{46}Sc, ^{48}V, ^{56}Co, ^{59}Fe, ^{74}As, ^{84}Rb, ^{86}Rb, ^{91}Y, ^{105}Ag, ^{115m}Cd, ^{124}Sb, ^{126}I, ^{129m}Te/^{129}Te, ^{131}Ba, ^{160}Tb	^{65}Zn, ^{106}Ru/^{106}Rh, ^{110m}Ag, ^{123}Sn, ^{144}Ce/^{144}Pr, ^{182}Ta	^{22}Na, ^{26}Al, ^{40}K, ^{60}Co, ^{134}Cs, ^{152}Eu, ^{154}Eu, ^{207}Bi, ^{226}Ra + D.P., ^{227}Ac + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{238}U/^{234m}Pa
^{72}As, ^{76}As, ^{82}Br, ^{124}I, ^{132}Cs, ^{140}La, ^{166}Ho, ^{206}Bi, ^{222}Rn + D.P.	^{56}Co, ^{58}Co, ^{84}Rb, ^{124}Sb, ^{140}Ba/^{140}La	^{88}Y, ^{106}Ru/^{106}Rh, ^{110m}Ag	^{26}Al, ^{152}Eu, ^{154}Eu, ^{207}Bi, ^{226}Ra + D.P., ^{228}Ra/^{228}Ac, ^{228}Th + D.P., ^{238}U/^{234m}Pa
^{72}As, ^{76}As, ^{124}I, ^{140}La, ^{206}Bi, ^{222}Rn + D.P.	^{48}V, ^{56}Co, ^{124}Sb, ^{140}Ba/^{140}La	^{88}Y, ^{106}Ru/^{106}Rh, ^{144}Ce/^{144}Pr	^{26}Al, ^{226}Ra + D.P., ^{228}Th + D.P.
^{72}As	^{56}Co		

Table 3.7 NUCLIDES FOR ALPHA SOURCES

Nuclide	*Half-life*	*α-energies* MeV	*Associated β and γ radiation* MeV
Americium-241	432.2 yr	5.44, 5.48	γ_{max} 0.060
Lead-210 (+daughters)	22.3 yr	5.305	β_{max} 1.17 γ_{max} 0.80 (very weak)
Plutonium-238	87.74 yr	5.352, 5.452, 5.495	γ 0.096 (very weak)
Plutonium-239	2.41×10^4 yr	5.096, 5.134, 5.147	γ_{max} 0.451 (weak)
Polonium-210	138.4 d	5.305	γ 0.80 (very weak)
Radium-226 (+daughters)	1 600 yr	4.589–7.68	β_{max} 3.26 γ_{max} 2.43

Table 3.8 NUCLIDES FOR BETA SOURCES

Nuclide	*Half-life*	β_{max} MeV	*Associated α and γ radiation* MeV
Carbon-14	5 730 yr	0.159	— —
Cerium-144 + praseodymium-144	284.3 d	2.98	γ 0.034–2.19
Iron-55	2.7 yr	0.0052	γ 0.005 9–0.006 5
Krypton-85	10.72 yr	0.67	γ 0.51
Lead-210 + bismuth-210	22.3 yr	1.17	α 5.30 γ_{max} 0.80 (very weak)
Nickel-63	96 yr	0.066	—
Promethium-147	2.62 yr	0.225	—
Ruthenium-106 + rhodium-106	368.2 d	3.6	γ 0.43–2.41
Strontium-90 + yttrium-90	29.12 yr	2.27	—
Thallium-204	3.78 yr	0.77	—
Tritium	12.35 yr	0.018	—
Yttrium-90	64.0 h	2.27	—

Table 3.9 NUCLIDES FOR NEUTRON SOURCES—POLONIUM-210 (ALPHA, N) SOURCES WITH VARIOUS TARGETS

Target	Neutrons s^{-1} TBq^{-1}	*Neutron energy* (MeV)	
		Mean	*Maximum*
Aluminium	5.4×10^5	—	2.7
Beryllium	6.8×10^7	4.3	10.8
Boron	5.4×10^6	—	5.0
Fluorine-19	2.7×10^6	1.4	2.8
Lithium	1.4×10^6	0.48	1.32
Magnesium	8.1×10^5	—	—
Oxygen-18	2.7×10^7	—	4.3
Sodium	1.1×10^6	—	—
Mock fission	1.1×10^6	1.6	10.8

Table 3.10 NUCLIDES FOR NEUTRON SOURCES—(GAMMA, N) SOURCES

Nuclide	*Half-life*	*Target*	*Observed* neutron s^{-1} TBq^{-1}	*Observed neutron energy* keV
Antimony-124	60.20 d	Beryllium	4.3×10^7	24.8
Radium-226 (+daughters)	1 600 yr	Beryllium	3.5×10^7	700 (max)
Radium-226 (+daughters)	1 600 yr	Deuterium (heavy water)	—	120
Thorium-228 (+daughters)	1.91 yr	Beryllium	—	827
Thorium-228 (+daughters)	1.91 yr	Deuterium (heavy water)	3.2×10^7	197

Table 3.11 NUCLIDES FOR NEUTRON SOURCES—(ALPHA, N) SOURCES WITH BERYLLIUM TARGETS

Nuclide	*Half-life*	Neutrons s^{-1} TBq^{-1}	*Gamma emission* $\mu Gy\ h^{-1}$ *at* 1 m *from* 10^6 neutrons s^{-1}
Actinium-227 (+daughters)	21.77 yr	4.9×10^8	80
Americium-241	432.2 yr	5.9×10^7	11.4
Lead-210 (+daughters)	22.3 yr	6.2×10^7	88
Plutonium-239	2.41×10^4 yr	3.8×10^7	17
Polonium-210	138.4 d	6.8×10^7	0.4
Radium-226 (+daughters)	1 600 yr	4.2×10^8	600
Thorium-228 (+daughters)	1.91 yr	6.8×10^8	300

Table 3.12 SPONTANEOUS FISSION NEUTRON SOURCE

Nuclide	*Half-life*	Neutrons s^{-1} mg^{-1}	*Gamma emission* $\mu Gy\ h^{-1}$ *at* 1 m *from* 10^6 neutrons s^{-1}
Californium-252	2.64 yr (effective)	2.3×10^9	0.7

REFERENCES

'Radionuclide Transformations, Energy and Intensity of Emissions', ICRP Publication 38, Pergamon, Oxford, 1983.
'Radioactive Decay Data Tables', DOE/TIC-11026, Technical Information Center, U.S. Department of Energy, 1981.

4 X-ray analysis of metallic materials

4.1 Introduction

X-rays are very short wavelength electromagnetic waves. Their range encompasses the interatomic distances in crystalline materials, typically 0.5 to 2.5 Å, which permit the analysis of crystalline and to a lesser degree amorphous materials by X-ray diffraction (XRD). When atoms are irradiated with radiation of sufficient energy, they emit characteristic X-ray spectra, fluorescence, which are analysed in X-ray fluorescent analysis (XRF) to give element analysis. Individual electrons are emitted from an irradiated surface with energies related to the electron levels in the atom. The energies of these electrons are analysed in X-ray photoelectron spectroscopy (XPS) to provide an elemental analysis of surface atoms together with information on the chemical bonding between them.

This chapter reviews the applications of XRD to the investigation of metallic materials. The subject is well covered in detail in several standard textbooks including 'X-ray Metallography' by A. Taylor[1]; 'Structure of Metals' by C. Barrett and T. B. Massalaski[2]; 'X-ray Diffraction Procedures' by H. P. Klug and L. E. Alexander.[3] The 'Proceedings of the Denver Annual Conferences on Application of X-ray Analysis'[4] are invaluable for keeping up with the continuous advances in both applications and equipment.

4.2 Excitation of X-rays

X-rays are produced (excited) when an electron experiences a sudden acceleration or (more commonly in practice) deceleration as, for example, when a beam of fast-moving electrons strikes an atom. If an electron is completely stopped by the impact, and its energy completely converted into radiation, an X-ray quantum will be emitted having frequency ν and wavelength λ given by the quantum relationship

$$E = Ve = h\nu = \frac{hc}{\lambda}$$

where E = energy of electron, V = accelerating voltage, e = charge on electron, h = Planck's constant, c = velocity of light: which, by substitution of numerical values, reduces to

$$\lambda = \frac{12.34}{V} \text{ Å}$$

where V is expressed in kilovolts.

In an X-ray tube, the energy of the electrons is converted immediately into radiation in only a few cases: most electrons undergo repeated collisions and dissipate the greater part of their energy as heat. In such cases the energy E available for radiation is reduced, and appears as X-rays of longer wavelength. The radiation is therefore not monochromatic, and the above equation gives the minimum wavelength occurring in the emergent beam, the so-called 'short wave cut-off'.

If the intensity of the radiation is plotted against the wavelength, for relatively low applied voltages a curve is obtained rising from zero to a more or less pronounced maximum, falling again to a low value with increasing wavelength. It has been found that for this curve of so-called 'white radiation' both the total radiation and the intensity of the peak are closely proportional to the

atomic number of the target material. Thus if white radiation is required a target of one of the heavy metals should be selected, and since the total intensity (the area under the curve) is proportional to the square of the applied voltage the latter should be as high as possible.

On increasing the voltage beyond a certain limit, which is different for different targets, a line spectrum begins to appear, superimposed upon the continuous or white spectrum, the wavelengths of the lines being constant and characteristic of the target. The lowest critical voltage at which these lines appear is that which endows the bombarding electrons with just sufficient energy to eject electrons from one of the inner shells in the target atoms. Each vacancy as it occurs is filled by an electron jumping in from one of the outer shells, the jump being accompanied by an emission of energy of frequency ν given by the Bohr relationship

$$h\nu = W_1 - W_2$$

where $W_1 - W_2$ represents the change in potential energy of the system and h is Planck's constant.

The K series of lines is excited when electrons are ejected from the K shell and their places taken by electrons from the L, M or N shells. It consists of four lines $K\alpha_1$, $K\alpha_2$, $K\beta_1$ and $K\beta_2$, the α lines being associated with jumps from the L shell, β_1 with those from the M shell, and β_2 with those for the N shell. Other series of lines are emitted when the bombarding electrons eject electrons from the L, M or N shells. The K emissions which are the most intense are generally used in XRD while all the spectra are employed in XRF.

If V_0 is the critical voltage at which the K spectra first appear and ε the electron mass, then the energy needed to remove an electron from the K shell is $V_0 e$ which is equivalent to radiation of frequency ν_0 and wavelength λ_0 given by

$$V_0 e = h\nu_0 = \frac{hc}{\lambda_0}$$

where c is the velocity of light. This critical wavelength, termed the K absorption edge of the material, together with slightly shorter wavelengths are heavily absorbed in the material. In XRD, to avoid fluorescence (high background) and low penetration into the sample a radiation is chosen which is on the long wavelength side of any absorption edge of the sample.

The empirical expression

$$I = K(V - V_0)^{1.7}$$

where K is a constant, relates the intensity, I, of the characteristic radiation to the difference between the tube voltage V and the critical voltage V_0 of the target material. It is found that the relative intensity of the characteristic radiation to that of the continuous wavelength (white) radiation is greatest for tube voltages of about four times the critical voltage. A method of achieving partial monochromatization of the X-ray beam is to reduce the intensity of the K_β radiation with respect to that of the K_α by using a filter of an element with K absorption edge between the K_β and K_α wavelengths. The thickness of the filter is usually chosen to reduce the intensity of K_β to about 1/600 of the transmitted K_α. Generally, the element preceding the target element in the periodic table will act as a K_β filter. Filters cannot separate the α_1 and α_2 components and where they are not resolved in a diffraction pattern, d values are calculated using a weighted average wavelength where α_1, the stronger of the two, is given twice the weight of α_2. Full monochromatization can be achieved with a single crystal monochromator oriented such that only $K_{\alpha_1\alpha_2}$ components are diffracted. Monochromators in the form of a single crystal lamina bent to produce focusing are widely used in diffractometry to remove all unwanted radiation. Construction of focusing monochromators is described in 'International Tables for X-ray Crystallography'.[5]

Table 4.1 lists wavelengths, minimum excitation potentials and K_β filters for targets frequently used in XRD. Table 4.2 gives minimum excitation potentials for characteristic K, L, M, and N spectra while Table 4.3 and 4.4 give K and L emission spectra and L_{111} absorption edges for all elements. Crystals suitable for monochromators are listed with comments on their performance in Table 4.5.

4.2.1 X-ray wavelengths

The X-unit defined by Siegbahn and very nearly equal to 10^{-3} Å was based on the atomic spacing in calcite as determined from the expression:

$$2d = \left(\frac{4M}{\rho NV}\right)^{1/3}$$

where M = molecular weight of calcite, ρ = density of calcite, N = Avogadro's number, V = volume of calcite rhombohedron with unit distance between the faces considered.

kX units were widely used up to about 1945 but were then gradually replaced by absolute Ångströms as more precise methods for determining X-ray wavelengths were introduced. The nanometer (10^{-9} m) is now declared to be the standard unit for X-ray studies. However, in view of the much greater familiarity with Å, and the very simple conversion factor, in this edition the Ångström unit is used unless the contrary is stated.

1 kX unit = 1.002 02 Ångström units
1 Ångström unit, Å = 10^{-10} m or 10^{-1} nanometers

Emission lines are frequently quoted in keV

$$1\,\text{keV} = \frac{12.3975}{\text{Wavelength in Å}}$$

Table 4.1 WAVELENGTHS, EXCITATION POTENTIALS, AND β FILTERS FREQUENTLY USED IN CRYSTALLOGRAPHIC WORK

Target					*β-filter*				
								Material content	
Element	*Atomic No.*	*Line*	*Wavelength** Å	*Excitation potential†* kV	*Element*	*Absorption edge*	*Mass absorption coefficient* μ/ρ	g cm^{-2}	*Thickness* mm
Cr	24	$K\alpha_1$	2.289 62	5.98	V	2.267 5	77.3	0.009	0.016
		$K\alpha_2$	2.293 51						
		$K\alpha$	2.290 9						
		$K\beta_1$	2.084 80						
Mn	25	$K\alpha_1$	2.101 75	6.54	Cr	2.070 1	71	0.011	0.016
		$K\alpha_2$	2.105 69						
		$K\alpha$	2.103 1						
		$K\beta_1$	1.910 15						
Fe	26	$K\alpha_1$	1.935 97	7.1	Mn	1.895 4	61.9	0.012	0.016
		$K\alpha_2$	1.939 91						
		$K\alpha$	1.937 3						
		$K\beta_1$	1.756 53						
Co	27	$K\alpha_1$	1.788 92	7.71	Fe	1.742 9	58.6	0.014	0.018
		$K\alpha_2$	1.792 78						
		$K\alpha$	1.790 2						
		$K\beta_1$	1.620 75						
Ni	28	$K\alpha_1$	1.657 84	8.29	Co	1.607 2	51.6	0.015	0.018
		$K\alpha_2$	1.661 69						
		$K\alpha$	1.659 1						
		$K\beta_1$	1.500 10						
Cu	29	$K\alpha_1$	1.540 51	8.86	Ni	1.486 9	48.0	0.019	0.021
		$K\alpha_2$	1.544 33						
		$K\alpha$	1.541 8						
		$K\beta_1$	1.392 17						
W	74	$L\alpha_1$	1.476 35	12.1	Cu	1.380 2	42.0	0.019	0.021
		$L\alpha_2$	1.487 42						
Zn	30	$K\alpha_1$	1.435 11	9.65	Cu	1.380 2	42.0	0.019	0.021
		$K\alpha_2$	1.438 94						
		$K\alpha$	1.436 4						
		$K\beta_1$	1.295 22						
Au	79	$L\alpha_1$	1.276 39	14.4	Ga	1.195 7	37.0	0.028	0.047
		$L\alpha_2$	1.287 77						
		$K\alpha_2$	0.785 88						
		$K\alpha_2$	0.790 10						
		$K\alpha$	0.787 29	80.5	Sr	0.769 69	18.1	0.053	0.210

Table 4.1 WAVELENGTHS, EXCITATION POTENTIALS, AND β FILTERS FREQUENTLY USED IN CRYSTALLOGRAPHIC WORK—*continued*

Target					*β-filter*				
								Material content	
Element	*Atomic No.*	*Line*	*Wavelength** Å	*Excitation potential†* kV	*Element*	*Absorption edge*	*Mass absorption coefficient* $\mu-\rho$	g cm^{-2}	*Thickness* mm
Zr	40	Kβ	0.701 70						
Mo	42	Kα_1	0.709 26	20	Zr	0.688 8	17.2	0.069	0.108
		Kα_2	0.713 54						
		Kα	0.710 7						
		Kβ_1	0.632 25						
Rh	45	Kα_1	0.613 25	23.2	Ru	0.559 5	15.4	0.077	0.064
		Kα_2	0.617 61						
		Kα	0.614 7						
		Kβ_1	0.545 59						
Pd	46	Kα_1	0.585 42	24.4	Rh	0.534 1	14.6	0.091	0.073
		Kα_2	0.589 80		or				
		Kα	0.586 9		Ru	0.559 5			
		Kβ_1	0.520 52						
Ag	47	Kα_1	0.559 36	25.5	Pd	0.509 0	13.1	0.096	0.079
		Kα_2	0.563 78		or				
		Kα	0.560 9		Rh	0.534 1			
		Kβ_1	0.497 01						

* λKα is here defined as $(2\lambda K\alpha_1 + \lambda K\alpha_2)/3$.

† The optimum voltage for operating a tube with raw alternating currents is approximately 5 times the excitation potential, and 4 times the excitation potential with fully smoothed direct current, but normally 80 kV cannot be exceeded owing to the danger of electrical breakdown.

Table 4.2 EXCITATION POTENTIALS IN kV FOR CHARACTERISTIC X-RAY SPECTRA

Atomic No. and element	K	L	M	N	*Atomic No. and element*	K	L	M	N
11 Na	1.07	—	—	—	49 In	27.80	4.21	0.83	0.12
12 Mg	1.30	—	—	—	50 Sn	29.06	4.42	0.88	0.13
13 Al	1.55	—	—	—	51 Sb	30.35	4.69	0.94	0.15
14 Si	1.83	—	—	—	52 Te	31.66	4.93	1.01	0.17
15 P	2.13	—	—	—	53 I	33.01	5.16	1.08	0.19
16 S	2.46	—	—	—	55 Cs	35.80	5.68	1.21	0.23
17 Cl	2.81	0.24	—	—	56 Ba	37.24	5.92	1.29	0.25
19 K	3.69	0.34	—	—	57 La	38.75	6.24	1.36	0.27
20 Ca	4.02	0.40	—	—	58 Ce	40.27	6.53	1.43	0.29
21 Sc	4.48	0.46	—	—	59 Pr	41.81	6.81	1.51	0.30
22 Ti	4.94	0.53	—	—	60 Nd	43.37	7.10	1.58	0.32
23 V	5.44	0.60	—	—	62 Sm	46.63	7.71	1.72	0.35
24 Cr	5.96	0.68	—	—	63 Eu	48.29	8.02	1.80	0.36
25 Mn	6.51	0.76	—	—	64 Gd	50.00	8.35	1.88	0.38
26 Fe	7.08	0.85	—	—	65 Tb	51.76	8.67	1.96	0.40
27 Co	7.67	0.92	—	—	66 Dy	53.55	9.01	2.04	0.42
28 Ni	8.29	1.01	—	—	67 Ho	55.36	9.35	2.13	0.43
29 Cu	8.94	1.10	—	—	68 Er	57.22	9.71	2.22	0.45
30 Zn	9.62	1.19	—	—	69 Tm	59.07	10.06	2.31	0.47
31 Ga	10.32	1.29	—	—	70 Yb	61.02	10.45	2.41	0.50
32 Ge	11.05	1.41	—	—	71 Lu	63.01	10.82	2.50	0.51
33 As	11.81	1.52	—	—	72 Hf	65.01	11.23	2.60	0.54
34 Se	12.59	1.65	—	—	73 Ta	67.09	11.63	2.69	0.57
35 Br	13.41	1.78	—	—	74 W	69.18	12.04	2.80	0.59
37 Rb	15.13	2.05	—	—	75 Re	71.28	12.46	2.91	—

Table 4.2 EXCITATION POTENTIALS IN kV FOR CHARACTERISTIC X-RAY SPECTRA—*continued*

Atomic No. and element	K	L	M	N	*Atomic No. and element*	K	L	M	N
38 Sr	16.03	2.20	—	—	76 Os	73.54	12.91	3.03	0.64
39 Y	16.96	2.38	—	—	77 Ir	75.77	13.35	3.15	0.67
40 Zr	17.92	2.52	0.43	0.05	78 Pt	78.02	13.80	3.28	0.71
41 Nb	18.90	2.69	0.48	0.05	79 Au	80.42	14.29	3.41	0.79
42 Mo	19.91	2.86	0.51	0.06	80 Hg	82.69	14.77	3.55	0.82
44 Ru	22.02	3.21	0.59	0.06	81 Tl	85.28	15.27	3.69	0.86
45 Rh	23.12	3.39	0.62	0.07	82 Pb	87.66	15.79	3.84	0.89
46 Pd	24.23	3.60	0.67	0.08	83 Bi	90.03	16.31	3.99	0.96
47 Ag	25.40	3.81	0.72	0.10	90 Th	109.27	20.36	5.17	1.33
48 Cd	26.59	4.00	0.77	0.11	92 U	115.54	21.66	5.54	1.44

Table 4.3 K EMISSION LINES AND K ABSORPTION EDGES IN Å

Line transition intensity rel. to $K\alpha_1$	α_2 KL_{11} 50	α_1 KL_{111} 100	β_3 $KM_{11}15$	β_1 KM_{111} 15	β_2 $KN_{11,111}$ 5	K *Absorption edge*
3 Li	228.0		—	—	—	226.5
4 Be	114.0		—	—	—	—
5 B	67.6		—	—	—	—
6 C	44.7		—	—	—	43.7
7 N	31.6		—	—	—	31.0
8 O	23.62		—	—	—	23.3
9 F	18.32		—	—	—	—
10 Ne	14.61		—	14.452	—	—
11 Na	11.910 [illegible]		—	11.575	—	—
12 Mg	9.890 0		—	9.521	—	9.511 7
13 Al	8.341 73	8.339 34	—	7.960	—	7.951 1
14 Si	7.127 91	7.125 42	—	6.753	—	6.744 6
15 P	6.160	6.157	—	5.796	—	5.786 6
16 S	5.374 96	5.372 16	—	5.032	—	5.018 2
17 Cl	4.730 7	4.727 8	—	4.403 4	—	4.396 9
18 A	4.194 74	4.191 80	—	3.886 0	—	3.870 7
19 K	3.744 5	3.741 4	—	3.453 9	—	3.436 45
20 Ca	3.361 66	3.358 39	—	3.089 7	—	3.070 16
21 Sc	3.034 2	3.030 9	—	2.779 6	—	2.757 3
22 Ti	2.752 16	2.748 51	—	2.513 91	—	2.497 3
23 V	2.507 38	2.503 56	—	2.284 40	—	2.269 0
24 Cr	2.293 61	2.289 70	—	2.084 87	—	2.070 1
25 Mn	2.105 78	2.101 82	—	1.910 21	—	1.896 4
26 Fe	1.939 98	1.936 04	—	1.756 61	1.744 2	1.743 3
27 Co	1,792 85	1.788 97	—	1.620 79	1.608 9	1.608 1
28 Ni	1.661 75	1.657 91	—	1.500 14	1.488 6	1.488 0
29 Cu	1.544 39	1.540 56	1.392 6	1.392 22	1.381 09	1.380 4
30 Zn	1.439 00	1.435 16	—	1.295 25	1.283 72	1.283 3
31 Ga	1.343 99	1.340 08	1.208 35	1.207 89	1.196 00	1.195 7
32 Ge	1.258 01	1.254 05	1.129 36	1.128 94	1.116 86	1.116 5
33 As	1.179 87	1.175 88	1.057 83	1.057 30	1.045 00	1.045 0
34 Se	1.108 82	1.104 77	0.992 68	0.992 18	0.979 92	0.979 78
35 Br	1.043 82	1.039 74	0.933 27	0.932 79	0.920 46	0.919 95
36 Kr	0.984 1	0.980 1	0.879 0	0.878 5	0.866 1	0.865 47
37 Rb	0.929 69	0.925 553	0.829 21	0.828 68	0.816 45	0.815 49
38 Sr	0.879 43	0.875 26	0.783 45	0.782 92	0.770 81	0.769 69
39 Y	0.833 05	0.828 84	0.741 26	0.740 72	0.728 64	0.727 62
40 Zr	0.790 15	0.785 93	0.702 28	0.701 73	0.689 93	0.688 77
41 Nb	0.750 44	0.746 20	0.666 34	0.665 76	0.654 16	0.652 91
42 Mo	0.713 59	0.709 30	0.632 87	0.632 29	0.620 99	0.619 77
43 Tc	0.679 32*	0.675 02*	0.601 88*	0.601 30*	0.590 24*	(0.589 1)
44 Ru	0.647 41	0.643 08	0.573 07	0.572 48	0.561 66	0.560 05

Table 4.3 K EMISSION LINES AND K ABSORPTION EDGES IN Å—*continued*

Line transition intensity rel. to $K\alpha_1$	α_2 KL_{11} 50	α_1 KL_{111} 100	β_3 KM_{11} 15	β_1 KM_{111} 15	β_2 $KN_{11,111}$ 5	K *Absorption edge*
45 Rh	0.617 63	0.613 28	0.546 20	0.545 61	0.535 03	0.533 8
46 Pd	0.589 82	0.585 45	0.521 12	0.520 52	0.510 23	0.509 2
47 Ag	0.563 80	0.559 41	0.497 69	0.487 07	0.487 03	0.485 8
48 Cd	0.539 42	0.535 01	0.475 73	0.475 10	0.465 33	0.464 09
49 In	0.516 54	0.512 11	0.455 18	0.454 54	0.445 00	0.443 88
50 Sn	0.435 24	0.425 92	0.424 67	0.431 84	0.431 75	0.424 68
51 Sb	0.474 83	0.470 35	0.417 74	0.417 09	0.407 97	0.406 63
52 Te	0.455 78	0.451 30	0.400 66	0.399 99	0.391 10	0.389 72
53 I	0.437 83	0.433 32	0.384 56	0.383 91	0.375 23*	0.373 79
54 Xe	0.420 87*	0.416 34~	0.369 41*	0.368 72~	0.360 26*	0.358 49
55 Cs	0.404 84	0.400 29	0.355 05	0.354 36	0.346 11	0.344 74
56 Ba	0.389 67	0.385 11	0.341 51	0.340 81	0.332 77	0.331 37
57 La	0.375 31	0.370 74	0.328 69	0.327 98	0.320 12	0.318 42
58 Ce	0.361 68	0.357 09	0.316 52	0.315 82	0.308 16	0.306 47
59 Pr	0.348 75	0.344 14	0.304 98	0.304 26	0.296 79	0.295 16
60 Nd	0.336 47	0.331 85	0.294 03	0.293 30	0.286 1*	0.284 51
61 Pm	0.324 80	0.320 16	0.283 63*	0.282 90*	0.275 9*	0.274 3
62 Sm	0.313 70	0.309 04	0.273 76	0.273 01	0.266 2	0.264 62
63 Eu	0.303 12	0.298 45	0.264 33	0.263 58	0.256 92	0.255 52
64 Gd	0.293 04	0.288 35	0.255 34	0.254 60	0.248 16	0.246 80
65 Tb	0.283 42	0.278 72	0.246 83	0.246 08	0.239 7*	0.238 40
66 Dy	0.274 25	0.269 53	0.238 62	0.237 88	0.231 7*	0.230 46
67 Ho	0.265 486	0.260 76	0.230 83	0.230 12	0.224 1*	0.222 90
68 Er	0.257 11	0.252 37	0.223 41	0.222 66	0.216 7*	0.215 66
69 Tm	0.249 10	0.244 34	0.216 36	0.215 56	0.209 8*	0.208 9
70 Yb	0.241 42	0.236 66	0.209 6*	0.208 84	0.203 3*	0.202 23
71 Lu	0.234 08	0.229 30	0.203 09*	0.202 31*	0.196 9*	0.195 84
72 Hf	0.227 02	0.222 22	0.196 86~	0.196 07	0.190 8*	0.189 81
73 Ta	0.220 31	0.215 50	0.190 89	0.190 09	0.185 10	0.183 93
74 W	0.213 83	0.209 01	0.185 18	0.184 37	0.179 51	0.178 37
75 Re	0.207 61	0.202 78	0.179 70	0.178 88	0.174 15	0.173 11
76 Os	0.201 64	0.196 79	0.174 43	0.173 61	0.169 90	0.167 80
77 Ir	0.195 90	0.191 05	0.169 37	0.168 54	0.164 05	0.162 86
78 Pt	0.190 38	0.185 51	0.164 50	0.163 68	0.159 29	0.158 16
79 Au	0.185 08	0.180 20	0.159 81	0.158 98	0.154 72	0.153 44
80 Hg	0.179 96	0.175 07	0.155 32	0.154 49	0.150 30	0.149 23
81 Tl	0.175 04	0.170 14	0.150 98	0.150 14	0.146 04	0.144 70
82 Pb	0.170 29	0.165 38	0.146 81	0.145 97	0.142 01	0.140 77
83 Bi	0.165 72	0.160 79	0.142 78	0.141 95	0.138 07	0.137 06
84 Po	0.161 30*	0.156 36*	0.138 92~	0.138 07~	0.134 28~	—
85 At	0.157 05~	0.152 10*	0.135 17*	0.134 32*	0.130 67~	—
86 Rn	0.152 94~	0.147 98*	0.131 55*	0.130 69~	0.127 08~	--
87 Fr	0.148 96*	0.143 99*	0.128 07*	0.127 19*	0.123 68	—
88 Ra	0.145 12*	0.140 14*	0.124 69*	0.123 82*	0.120 39	—
89 Ac	0.141 41~	0.136 42~	0.121 43*	0.120 55*	0.117 21*	—
90 Th	0.137 83	0.132 81	0.118 27	0.117 40	0.114 15*	0.112 93
91 Pa	0.134 34*	0.129 33*	0.115 23*	0.114 35*	0.111 18*	—
92 U	0.130 97	0.125 95	0.112 30	0.111 39	0.108 27*	0.106 80

* Interpolated values.

Table 4.4 EMISSION SPECTRA AND ABSORPTION EDGES IN Å

Line	l	η	α_2	α_1	β_1	β_4	β_3	β_2	β_5	γ_1	*Absorption edges*		
transition	LiiiMi	LiiMi	LiiiMiv	LiiiMv	LiiMiv	LiMii	LiMiii	LiiiNv	LiiOiv, v	LiiNiv			
intensity rel. to α_1	30	10	10	100	80	20	30	60	60	40	LI	LII	LIII
17 Cl	67.90	67.33				–	—	—	—	—	52.084	61.366	61.672
18 A	56.30[1]	55.9[1]				—	—		—	—	43.192	50.390	50.803
19 K	47.74	47.24		—		–	—	—	—	—	36.352	42.020	42.452
20 Ca	40.96	40.46	36.33			—	—	—			31.068	35.417	35.827
21 Sc	35.59	35.13	31.35		31.02	—	—				26.831	30.161	30.457
22 Ti	31.36	30.89	27.42		27.05						23.389	26.831	27.184
23 V	27.77	27.34	24.25		23.88	—	—	—	—		20.523	23,702	24,070
24 Cr	24.78	24.30	21.64		21.27	—	–				18.256	21.226	21.596
25 Mn	22.29	21.85	19.45		19.11	—	—	—			16.268	18.896	19.248
26 Fe	20.15	19.75	17.59		17.26	—	—	—			14.601	17.169	17.484
27 Co	18.292	17.87	15.972		15,666	—		—			13.343	15 534	15.831
28 Ni	16.693	16.27	14.561		14,271	—		—		—	12,267	14,135	14,448
29 Cu	15.286	14.90	13.336		13.053	—	–	—	—	—	11.269	12.994	13.258
30 Zn	14.02	13.68	12.254		11,983	—	—		—		10.330	11.840	12.106
31 Ga	12.953	12.597	11.292		11.023	—	—		—		9.535	10.613	10.855
32 Ge	11.965	11.609	10.436 1		10,175	–	–	—		—	8.729	9.965	10.228
33 As	11.072	10.734	9.670 9		9.414 1	—	—	—	—	—	8.107	9.128 1	9.376 7
34 Se	10.294	9.962	8.990 0		8.735 8	—	–	—	–	–	7.467	8.421 2	8.662 4
35 Br	9.585	9.255	8.374 6		8,125 1	—	–	—	–		6,925	7.752 3	7.987 1
36 Kr	—	—	7.817[2]		7.576[2]	–	—	—	–	–	6.456	7.165 3	7.422 7
37 Rb	8.363 6	8.041 5	7.325 1	7.318 3	7.075 9	6.820 7	6.787 6	—	—	—	6.006	6.653 8	6.875 2
38 Sr	7.836 2	7.517 1	6.869 7	6.862 8	6.623 9	6.402 6	6 367 2	–	—	–	5.604	6.185 6	6.399 6
39 Y	7.356 3	7.040 6	6.455 8	6.448 8	6.212 0	6.018 6	5.983 2	—		—	5.193 1	5.709 8	5.914 1
40 Zr	6.918 5	6.606 9	6.077 8	6.070 5	5.836 0	5.668 1	5.633 0	5.586 3	–	5.384 3	4.893 8	5.370 9	5.573 7
41 Nb	6.517 6	6.210 9	5.731 9	5.724 3	5.492 3	5.345 5	5.310 2	5.237 9	—	5.036 1	4,591 1	5.024 7	5.226 0
42 Mo	6.150 8	5.847 5	5.414 4	5.406 6	5.177 1	5.048 8	5.013 3	4.923 2		4.725 8	4.320 7	4.713 3	4.909 3
43 Tc		–		5.114 8[1]	4.887 3[2]	–	–	—			4.064 3	4.427 1	4.625 4
44 Ru	5.503 5	5.205 0	4.853 8	4.845 8	4.620 6	4.523 0	4.486 6	4.371 8	—	4.182 2	3.841 3	4.176 5	4.366 3
45 Rh	5.216 9	4.921 7	4.605 5	4.597 4	4.374 1	4.288 8	4.252 2	4.131 0	–	3.943 7	3,641 6	3.949 0	4.138 9
46 Pd	4.952 5	4.660 5	4.375 9	4.367 7	3.990 2	4.071 1	4.034 6	3,908 9		3.724 6	3.430 0	3 713 6	3.896 9

Table 4.4 L EMISSION SPECTRA AND ABSORPTION EDGES IN Å—*continued*

Line transition intensity rel. to α_1	l Liii Mi 30	η Lii Mi 10	α_2 Liii Miv 10	α_1 Liii Mv 100	β_1 Lii Miv 80	β_4 Li Mii 20	β_3 Li Miii 30	β_2 Liii Nv 60	β_5 Liii Oiv, v 60	γ_1 Lii Niv 40	L *Absorption edges* Li	Lii	Liii
47 Ag	4.707 6	4.418 3	4.162 9	4.154 4	3.934 7	3.870 2	3.833 1	3.703 4	—	3.522 6	3.238 2	3.494 8	3.672 9
48 Cd	4.480 1	4.193 2	3.965 0	3.956 4	3.738 2	3.682 0	3.645 0	3.514 1	—	3.335 6	3.084 3	3.322 4	3.500 7
49 In	4.268 7	3.983 3	3.780 7	3.771 9	3.555 3	3.507 0	3.469 8	3.338 4	—	3.162 1	2.933 3	3.155 0	3.321 5
50 Sn	4.071 7	3.788 8	3.608 9	3.599 9	3.384 9	3.343 4	3.305 9	3.175 1	—	3.001 2	2.788 8	2.994 9	3.169 5
51 Sb	3.888 3	3.607 7	3.448 4	3.439 4	3.225 7	3.190 1	3.152 6	3.023 4	—	2.851 6	2.633 0	2.823 0	2.996 4
52 Te	3.717 0	3.438 3	3.298 5	3.289 2	3.076 8	3.046 6	3.008 9	2.882 2	—	2.712 4	2.502 7	2.682 5	2.851 6
53 I	3.557 5	3.279 8	3.157 9	3.148 6	2.937 4	2.912 1	2.874 3	2.750 5	—	2.582 4	2.389 8	2.553 2	2.719 0
54 Xe	—	—	—	3.016 6*	—	—	—	—	—	—	2.274 5	2.430 6	2.593 3
55 Cs	3.267 0	2.993 2	2.902 0	2.892 4	2.683 7	2.666 6	2.628 5	2.511 8	—	2.348 0	2.172 5	2.312 7	2.472 3
56 Ba	3.135 5	2.862 7	2.785 5	2.776 0	2.568 2	2.555 3	2.516 4	2.404 4	—	2.241 5	2.083 4	2.202 2	2.361 1
57 La	3.006	2.740	2.675 3	2.665 7	2.458 9	2.449 3	2.410 5	2.303 0	—	2.141 8	1.978 9	2.100 3	2.257 9
58 Ce	2.891 7	2.620 3	2.570 6	2.561 5	2.356 1	2.349 7	2.310 9	2.208 7	—	2.048 7	1.890 8	2.009 4	2.164 1
59 Pr	2.784 1	2.512	2.472 9	2.463 0	2.258 8	2.255 0	2.217 2	2.119 4	—	1.961 1	1.813 1	1.923 1	2.077 1
60 Nd	2.676 0	2.409 4	2.380 7	2.370 4	2.166 9	2.166 9	2.126 8	2.036 0	—	1.877 9	1.737 6	1.842 4	1.994 5
61 Pm	—	—	2.292 6	2.282 2	2.079 7	—	2.042 1	1.955 9	—	1.798 9	1.668 4	1.765 8	1.918 9
62 Sm	2.482 3	2.218 2	2.210 6	2.199 8	1.998 1	2.001 0	1.962 4	1.882 2	1.847 0	1.727 2	1.601 1	1.694 4	1.844 6
63 Eu	2.394 8	2.131 5	2.131 5	2.120 9	1.920 3	1.925 5	1.886 7	1.811 8	1.777 2	1.657 4	1.538 2	1.625 9	1.774 9
64 Gd	2.312 2	2.049 4	2.057 8	2.046 8	1.846 8	1.854 0	1.815 0	1.745 5	1.713 0	1.592 4	1.478 7	1.560 8	1.709 6
65 Tb	2.235 2	1.973 0	1.987 5	1.976 5	1.776 8	1.786 4	1.747 2	1.683 0	1.651 0	1.530 3	1.422 7	1.501 1	1.648 4
66 Dy	2.158 9	1.897 4	1.919 9	1.908 8	1.710 6	1.721 0	1.682 2	1.623 7	1.588 4	1.472 7	1.369 3	1.443 6	1.590 3
67 Ho	2.086 0	1.826 4	1.856 1	1.845 0	1.647 5	1.659 5	1.620 3	1.567 1	1.537 8	1.417 4	1.319 4	1.390 0	1.535 3
68 Er	2.015	1.756 6	1.795 5	1.784 3	1.587 3	1.600 7	1.561 6	1.514 0	1.484 8	1.364 1	1.270 9	1.337 2	1.482 4
69 Tm	1.955 0	1.696 3	1.738 1	1.726 8•	1.530 4	1.544 8	1.506 3	1.464 0	1.434 9	1.315 3	1.227 1	1.288 6	1.431 4
70 Yb	1.894 2	1.635 6	1.682 9	1.671 9	1.475 7	1.491 4	1.452 3	1.415 5	1.387 0	1.267 7	1.181 4	1.241 5	1.385 2
71 Lu	1.836 0	1.577 9	1.630 3	1.619 5	1.423 6	1.440 6	1.401 4	1.370 1	1.341 8	1.222 3	1.140 1	1.197 5	1.340 4
72 Hf	1.781 5	1.523 3	1.580 5	1.569 6	1.374 1	1.392 2	1.353 0	1.326 4	1.297 6	1.179 0	1.098 6	1.153 1	1.295 7
73 Ta	1.728 4	1.471 1	1.532 9	1.522 0	1.327 0	1.345 8	1.306 8	1.284 5	1.255 5	1.137 9	1.060 8	1.112 6	1.254 3
74 W	1.678 2	1.421 1	1.487 4	1.476 4	1.281 8	1.301 6	1.262 7	1.244 6	1.215 5	1.098 6	1.025 0	1.074 4	1.215 3
75 Re	1.630 6	1.373 4	1.444 0	1.432 9	1.238 6	1.259 2	1.220 3	1.206 6	1.177 2	1.061 0	0.990 1	1.036 5	1.177 2
76 Os	1.585 0	1.327 9	1.402 3	1.391 2	1.197 3	1.218 4	1.179 6	1.169 8	1.140 5	1.025 0	0.955 7	1.001 3	1.141 4

77 Ir	1.5409	1.2845	1.3625	1.3513	1.1578	1.1796	1.1409	1.1353	1.1059	0.9909	0.92425	0.96700	1.1060
78 Pt	1.4995	1.2429	1.3243	1.3130	1.1199	1.1422	1.1039	1.1020	1.0724	0.9580	0.89405	0.93484	1.0731
79 Au	1.4596	1.2027	1.2877	1.2764	1.0835	1.1065	1.0679	1.0702	1.0404	0.9265	0.86378	0.90277	1.0403
80 Hg	1.4216	1.164	1.2526	1.2412	1.0487	1.0722	1.0336	1.0398	1.0099	0.8965	0.83531	0.87790	1.0094
81 Tl	1.3848	1.1277	1.2188	1.2074	1.0151	1.0392	1.0006	1.0103	0.9806	0.8675	0.80787	0.84355	0.97968
82 Pb	1.3499	1.0924	1.1865	1.1750	0.9829	1.0075	0.9691	0.9822	0.9526	0.8397	0.78153	0.81552	0.95112
83 Bi	1.3161	1.0586	1.1554	1.1439	0.9520	0.9769	0.9386	0.9552	0.9256	0.8131	0.75649	0.78910	0.92459
84 Po	1.2829	—	1.1255†	1.1139	0.9220	0.9475	0.9091	0.9294	0.8996	0.7875	0.73219	0.76377	0.89761
85 At	—	—	1.0967†	1.0850†	0.8935†	—	0.8814†	—	—	0.7629	0.70915	0.73873	0.87234
86 Rn	—	—	1.0690†	1.0572†	0.8661†	—	0.8544†	—	—	0.7393†	0.68675	0.71529	0.84845
87 Fr	—	—	1.0423	1.0305	0.8394	—	0.8279†	0.858	—	0.7165†	0.66537	0.69290	0.82529
88 Ra	1.167 2	0.9074	1.0166	1.0047	0.8138	0.8407	0.8027	0.8354	0.8063	0.6946	0.64461	0.67114	0.80284
89 Ac	—	—	0.9918†	0.9799†	0.7890†	—	0.7782†	—	—	0.6735†	0.6248	0.6500	0.7816
90 Th	1.1151	0.8545	0.9679	0.9560	0.7652	0.7926	0.7548	0.7935	0.7647	0.6531	0.6061	0.6301	0.7615
91 Pa	1.0908	0.8295	0.9448†	0.9328	0.7423	0.7699	0.7323	0.7737	0.7452	0.6336†	0.5875	0.6106	0.7414
92 U	1.0671	0.8051	0.9226	0.9106	0.7200	0.7480	0.7103	0.7547	0.7263	0.6148	0.5697	0.5919	0.7223
93 Np	1.0428	0.7809	0.9011	0.8891	0.6985	0.7267	0.6892	0.7362	0.7081	0.5965	0.5531	0.5742	0.7039
94 Pu	1.0226	0.7591	0.8803	0.8683	0.6777	0.7062	0.6687	0.7185	0.6907	0.5789	0.5366	0.5571	0.6864

†Interpolated values.

Table 4.5 CRYSTALS FOR PRODUCING MONOCHROMATIC X-RAYS

			Properties of reflection		*Properties of crystal*			
Crystal	*Reflection*	*Spacing* Å	*Peak intensity*	*Breadth*	*Crystal imperfection*	*Stability*	*Mechanical properties*	*Special uses*
β alumina	0 0 0 2 0 0 0 4	11.24 5.62	Weak Weak–medium	Moderate	Great	Perfect	Hard, brittle	For long wavelengths, but usable crystals hard to obtain
Mica	001 004	10.1 2.53	Weak	Small	Negligible for selected specimens	Fair	Flexible, easily cleaved	For point-focusing devices; exhibits irradiation effects
Gypsum	020	7.60	Medium–strong	Very small	Good specimens hard to find	Poor	Soft, flexible	For small-angle scattering; focusing long wavelengths
Pentaerythritol	002	4.40	Very strong	Moderate	Great	Poor	Soft, easily deformed	General purposes; exhibits irradiation effects
Quartz	1 0 1 1	3.35	Weak–medium	Very small	Negligible	Perfect	Can be elastically bent	For small-angle scattering; focusing
Potassium bromide	200	3.29	Medium–strong	Moderate	Negligible	Slightly deliquescent	—	—
Fluorite	111 220	3.16 1.94	Medium–strong Very strong	Moderate	Small	Perfect	Moderately hard	For eliminating harmonics; general purposes; short wavelengths
Urea nitrate	002	3.14	Strong	Very large	Very great	Very poor	Very easily deformed	For large specimens; soon decays
Calcite	200	3.04	Medium	Small	Negligible	Perfect	Moderately soft	For small-angle scattering; isolation of α_1 or α_2
Rock salt	200	2.82	Medium–strong	Large	Great	Slightly deliquescent	Can be plastically bent in warm supersaturated saline	For focusing
Aluminium	111	2.33	Very strong	Moderate to large	—	Good	Soft, can be seeded and grown to shape, then plastically shaped at room temperature	For focusing; diffuse scattering
Diamond	111	2.05	Weak	Very small	Negligible	Perfect	Very hard	For eliminating harmonics
Lithium fluoride	200	2.01	Very strong	Small-moderate	Negligible	Perfect	Hard, can be plastically bent at high temperature	For focusing; diffuse scattering; general purposes
Graphite	002	3.35	Very strong	Small	Negligible	Perfect	Easily shaped	Widely used for monochromators on diffractometers

4.3 X-ray techniques

The techniques, involving X-rays, which are commonly employed in the investigation of metallic materials are X-radiography, X-ray diffraction analysis, X-ray small angle scattering, X-ray fluorescence, and X-ray photoelectron spectroscopy (XPS). The basis of these techniques and their metallurgical applications are given in Table 4.6.

4.3.1 X-ray diffraction

Diffraction effects are produced when a beam of X-rays passes through the three-dimensional array of atoms which constitutes a crystal. Each atom scatters a fraction of the incident beams, and if certain conditions are fulfilled then the scattered waves reinforce to give a diffracted beam. These conditions are expressed by the Bragg equation:

$$n\lambda = 2d_{hkl} \sin \theta$$

where n is an integer, λ the wavelength of the incident beam, d_{hkl} the interplanar spacing of the hkl planes, and θ the angle of incidence on the hkl planes.

A randomly oriented single crystal irradiated with monochromatic radiation is unlikely to have any planes at the correct orientation to satisfy the Bragg equation. Hence when single crystals or more usually individual grains are examined they are either rotated in the X-ray beam or continuous wavelength (white) radiation is used as in the Laue technique.

In the case of powder or fine grained material sufficient crystals are irradiated for some to have planes oriented to satisfy the Bragg equation. The number is increased by rotating or translatng the specimen. A series of concentric diffraction cones with semiapex angle 2θ are produced which intersect a narrow film placed around the specimen in a series of arcs, which is the diffraction pattern. This is either recorded on film or scanned with an electronic radiation detector.

4.3.1.1 Experimental Methods

The experimental methods of X-ray diffraction and their common metallurgical applications are reviewed in Table 4.7. Film methods are included (only to illustrate particular applications) as they have virtually been replaced by computer automated diffractometer methods. Fully automated diffractometer systems are now commercially available for all XRD applications, ranging from routine rapid qualitative and quantitative analysis to detailed single crystal structure analysis.

With these systems, diffraction data are collected and processed automatically, peaks are identified and 2θ, d, peak intensity and width and integrated intensities are measured.

The data are stored in preparation for further evaluation specific to the applications, for example phase analysis and quantification, crystallite size and strain determination from peak breadths and crystallographic evaluations. These are obtained from the determination of unit cell, indexing of peaks and lattice parameter measurements.

The speed of data collection can be increased some 50 to 100 fold by replacing the scintillation counter previously supplied as the standard detector on conventional diffractometers with a Position Sensitive Detector (PSD). With this conversion a complete diffraction pattern can be obtained in a few minutes. The increase in speed is achieved by simultaneously recording diffractions over a 2θ range of about 12° as compared with only, typically, 0.05° with a conventional detector. There are two different modes of operation, stationary and scanning. In the stationary mode diffractions over a 2θ range of about 12° are simultaneously recorded, similar to, but much faster than recording on film. In the scanning mode, the detector is moved round the 2θ circle like a conventional detector. The scanning mode is often called Continuous Position Sensitive Proportional Counter (CPSC).[6]

Particular applications of each mode are:

Stationary mode—small angle scattering
phase transition
residential stress determination

Scanning mode—to produce a rapid throughput of specimens
phase transition where a complete diffraction pattern is needed
use with a high temperature chamber

Table 4.6 METALLURGICAL INVESTIGATION TECHNIQUES INVOLVING X-RAYS

Technique	*Principle of technique*	*Metallurgical applications*
X-radiography	Sample placed between divergent X-ray beam and detector (usually a photographic film). Dark areas on negative show regions of low X-ray absorption (i.e. low density in specimen such as cracks) and vice versa	Crack and other defect detection in castings, welded fabrications, etc. Very widely used inspection and quality assurance technique
X-ray diffraction	Beam of X-rays of specific wavelength (λ) diffracted at certain angles (θ) by crystal planes of appropriate spacing (d) which satisfies the Bragg equation, i.e.	Identification and quantitative analysis of crystalline chemical compounds (phase analysis and quantification, e.g. retained austenite determination)
	$n\lambda = 2d \sin \theta$	Crystal structure determination
	Angular position of diffraction peaks, shape of peaks, and intensity peaks give information on crystal structure and physical state	**Residual macro- and micro-stress analysis crystallite size** Texture (preferred grain orientation) measurement Detection of cold work and imperfections (by stacking faults, etc.) N.B. All results obtained from thin (typically 50 μm) surface layer
Small angle X-ray scattering	Large regions (e.g. 10 – > 10 000 Å) of inhomogeneous electron density distributions (e.g. vacancy clusters or Guinier–Preston zones) cause scattered radiation pattern near main beam	Determination of size, shape and composition (in terms of electron density) of Guinier–Preston zones, vacancy clusters, etc. in metallic transmission technique therefore limited to thin samples· typically 10–50 μm
X-ray fluorescence	Electrons ejected from inner shells of atoms cause emission of X-rays (fluorescence) characteristic of atomic species — exciting radiation may be photons (γ and X-rays), positive ions or electrons. Fluorescent X-rays analysed by wavelength or energy dispersive spectrometers.	Elemental analyses Na to U routine. C, N, O, F require specifically designed equipment. Hence used for routine analysis of composition of ores, semi-finished and finished metals and their alloys Quantitative analysis normally employs calibrated standards. N.B. Results are obtained from surface layer of approx. 2um thickness
X-ray photo-electron spectroscopy (XPS)	Electrons from inner shells of atoms are ejected by X-radiation of specific wavelength. Energy of ejected electron measured by spectrometer gives information on binding energy of electron shells	Qualitative and quantitative analysis of surface layers, XPS signals typically come from depths of less than 50 Å. Elemental analysis He to U including, C, N, O, F. Information on the state of bonding of analysed elements

Table 4.7 X-RAY DIFFRACTION TECHNIQUES

	Experimental Technique	*Description*	*Metallurgical applications*
SINGLE CRYSTAL	Single-crystal camera Weissenberg camera Precession camera Automated single crystal diffractometer	Small single crystal or metallic grains oriented on a two-axis goniometer with a prominent crystallographic axis along the goniometer axis. Crystal rotated in a monochromatic or filtered X-ray beam. Produces a spot diffraction pattern related to the symmetry of the crystal.	Determination of unit cell dimensions Crystal structure analysis (i.e. determination of atom positions and thermal vibrations) etc.
	Back reflection or transmission Laue camera	Stationary sample, single crystal or polycrystalline irradiated with white, continuous wavelength radiation. The back scattered, (back reflection) and forward scattered transmission diffraction patterns are recorded on flat films perpendicular to the incident beam. The symmetry of the diffraction pattern is related to the symmetry of the crystal in the beam direction. The transmission pattern can be electronically recorded on recently introduced (1991) large-area detectors.	Texture studies on deformed (worked) metallic materials Confirmation of crystal symmetry Determination of crystal orientation
POWDER OR FINE-GRAINED SAMPLE	Debye-Scherrer camera	Cylindrical compact of powder or wire sample (approx. 5 mm long and 0.5–1 mm in diameter) rotated (to avoid texture effects) in monochromatic X-ray beam. Diffraction cones intersect narrow cylindrical film (coaxial with sample) to give line spectrum	Phase identification Quantitative analysis of mixtures of chemical compounds usually with aid of calibrated standards Composition of alloy phases by correlation of lattice parameters with varying constituent elements
	Glancing angle camera	Diffraction spectra obtained by irradiating surface or edge sample at glancing angle and recording one half of total diffraction spectra (other half absorbed by sample) on photographic film	Examination of bulk samples, simultaneous detection and analysis of surface film (e.g. oxides) and parent metal substrate
	Guinier camera	Flat sample positioned on the circumference of the camera is irradiated by a monochromatic or filtered beam of X-rays diverging from a film around the circumference.	Improved resolution and inherently low background aids identification and comparison of specimens with small differences of structure. Diffractions at low Bragg angles (high d values) can be studied
	Diffractometry	Flat sample irradiated by a diverging beam of monochromatic or filtered X-rays. Detector rotated at twice the angular speed of the specimen to maintain the Bragg-Brentano focusing conditions	Phase identification and quantification (usually with calibrated standards) Studies of crystal imperfections, e.g. stacking faults, microstrain, etc. by detailed measurement of spectra profiles With appropriate attachments the following are possible: Residual stress measurement Texture (preferred orientation) determination Thermal expansion parameter measurement Phase transition monitoring

4.3.1.2 Accessory Attachments for Diffractometers

The range of applications of diffractometers is increased by accessory attachments for particular applications. These include:

- Specimen holder with rotation and translation scanning for analysing coarse grained solid and powder samples.
- Specimen changers for the sequential analysis of up to 40 specimens.
- Chambers for high and low temperature measurement. Temperature control and data collection can be automated and with a CPSC, rapid data collection system, a 3D display of 2θ and intensity against temperature can be obtained in a few hours.
- Preferred orientation is measured with a Texture Attachment. Intensity data are automatically collected and results displayed as either a conventional pole figure or as orientation distribution functions (ODF).[21]
- Attachments for quantitatively measuring residual stress.
- Diffraction patterns can be obtained from thin surface films by irradiating the surface at a shallow angle to increase the effective thickness of the film.

4.3.2 Specific Applications

4.3.2.1 Phase identification and quantitative measurements

Phase identification and quantification depend on the accurate measurement of the interplanar (d) spacings and relative intensities of the diffractions in a diffraction pattern. For routine phase identification the observed d spacings and relative intensities are compared with standard X-ray data listed in the X-ray Powder Diffraction File (PDF) published by the Joint Committee on Powder Diffraction Standards (JCPDS).[7] The file contains data for over 40 000 materials and is regularly updated. It can be obtained on computer files for computer search and match procedures which have virtually replaced the previously used manual procedures.

Interactive graphic search programmes are commonly employed. After entering any chemical information, the PDF files are automatically searched and possible matches listed. These are subsequently subtracted from the unknown pattern and the residual displayed for further analysis. With a mixture, the intensities of the file patterns can be varied to produce the best fit.

In practice, the success in analysing a mixture often depends on the availability of additional information. For example chemical analysis of individual phases or particles carried out by EDAX in a SEM, or a manual separation of phases for separate XRD analysis. The patterns can then be subtracted from the unknown pattern.

Quantitive determinations are carried out by comparing integrated intensities of selected diffractions. In order to allow for absorption, powders are usually analysed by adding a known fraction of standard calibrating powder and comparing the intensities of a diffraction from the component to be analysed with the intensity of a diffraction from the internal standard. Methods are thoroughly discussed in references 3, 9, 10 and 11.

X-ray diffraction analysis is used for the identification of atmospheric pollutants. Examples include silica[8] and asbestos particles collected on multipore filters. The method requires the taking of an X-ray scan directly from the filter and determining the amount of pollutant by comparison with calibration curves prepared from similar filters containing known amounts of the pollutants. As little as $2\,\mu g\,cm^{-2}$ of silica can be detected by this method.

Most metallurgical samples of interest, however, are solid and cannot be analysed by the above methods. In this case either a calibration curve is constructed from well characterized standards, showing, for precisely defined diffraction conditions, the variation in intensity of a particular diffraction with percentage of the phase to be analysed. Alternatively, theoretical intensities are calculated for diffractions from each phase to be analysed and the ratios of their amounts determined from the observed intensity ratios. The method is illustrated below for the determination of retained austenite in steels but can be extended to other systems. X-ray data for calculating diffraction intensities are listed in Tables 4.8, 4.9, 4.10 and 4.11.

Table 4.8 ANGLES BETWEEN CRYSTALLOGRAPHIC PLANES IN CRYSTALS OF THE CUBIC SYSTEM

(*HKL*)	(*hkl*)	*Values of α, the angle between (HKL) and (hkl)*						
100	100	0°	90°					
	110	45°	90°					
	111	54° 44′						
	210	26° 34′	63° 26′	90°				
	211	35° 16′	65° 54′					
	221	48° 11′	70° 32′					
	310	18° 26′	71° 34′	90°				
	311	25° 14′	72° 27′					
	320	33° 41′	56° 19′	90°				
	321	36° 43′	57° 42′	74° 30′				
110	110	0°	60°	90°				
	111	35° 16′	90°					
	210	18° 26′	50° 46′	71° 34′				
	211	30°	54° 44′	73° 13′	90°			
	221	19° 28′	45°	76° 22′	90°			
	310	26° 34′	47° 52′	63° 26′	77° 5′			
	311	31° 29′	64° 46′	90°				
	320	11° 19′	53° 58′	66° 54′	78° 41′			
	321	19° 6′	40° 54′	55° 28′	67° 48′	79° 6′		
111	111	0°	70° 32′					
	210	39° 14′	75° 2′					
	211	19° 28′	61° 52′	90°				
	221	15° 48′	54° 44′	78° 54′				
	310	43° 5′	68° 35′					
	311	29° 30′	58° 31′	79° 58′				
	320	61° 17′	71° 19′					
	321	22° 12′	51° 53′	72° 1′	90°			
210	210	0°	36° 52′	53° 8′	66° 25′	78° 28′	90°	
	211	24° 6′	43° 5′	56° 47′	79° 29′	90°		
	221	26° 34′	41° 49′	53° 24′	63° 26′	72° 39′	90°	
	310	8° 8′	58° 3′	45°	64° 54′	73° 34′		
	311	19° 17′	47° 36′	66° 8′	82° 15′			
	320	7° 7′	29° 45′	41° 55′	60° 15′	68° 9′	75° 38′	82° 53′
	321	17° 1′	33° 13′	53° 18′	61° 26′	70° 13′	83° 8′	90°
211	211	0°	33° 33′	48° 11′	60°	70° 32′	80° 24′	
	221	17° 43′	35° 16′	47° 7′	65° 54′	74° 12′	82° 12′	
	310	25° 21′	49° 48′	58° 55′	75° 2′	82° 35′		
	311	19° 8′	42° 24′	60° 30′	75° 45′	90°		
	320	25° 9′	37° 37′	55° 33′	63° 5′	83° 30′		
	321	10° 54′	29° 12′	40° 12′	49° 6′	56° 56′		
		70° 54′	77° 24′	83° 44′	90°			
221	221	0°	27° 16′	38° 57′	63° 37′	83° 37′	90°	
	310	32° 31′	42° 27′	58° 12′	65° 4′	83° 57′		
	311	25° 14′	45° 17′	59° 50′	72° 27′	84° 14′		
	320	22° 24′	42° 18′	49° 40′	68° 18′	79° 21′	84° 42′	
	321	11° 29′	27° 1′	36° 42′	57° 41′	63° 33′	74° 30′	
		79° 44′	84° 53′					
310	310	0°	25° 51′	36° 52′	53° 8′	72° 33′	84° 16′	
	311	17° 33′	40° 17′	55° 6′	67° 35′	79° 1′	90°	
	320	15° 15′	37° 52′	52° 8′	74° 45′	84° 58′		
	321	21° 37′	32° 19′	40° 29′	47° 28′	53° 44′	59° 32′	
		65°	75° 19′	85° 9′	90°			
311	311	0°	35° 6′	50° 29′	62° 58′	84° 47′		
	320	23° 6′	41° 11′	54° 10′	65° 17′	75° 28′	85° 12′	
	321	14° 46′	36° 19′	49° 52′	61° 5′	71° 12′	82° 44′	
320	320	0°	22° 37′	46° 11′	62° 31′	67° 23′	72° 5′	90°
	321	15° 30′	27° 11′	35° 23′	48° 9′	53° 37′	58° 45′	63° 36′
		72° 45′	77° 9′	85° 45′	90°			
321	321	0°	21° 47′	31°	38° 13′	44° 25′	50°	60°
		64° 37′	69° 4′	73° 24′	81° 47′	85° 54′		

Table 4.9 SYMMETRY INTERPRETATIONS OF EXTINCTIONS*

Class of reflection	*Condition for non-extinction (n = an integer)*	*Interpretation of extinction*	*Symbol of symmetry element*
hkl	$h+k+l=2n$	Body centred lattice	*I*
	$h+k=2n$	*C*-centred lattice	*C*
	$h+l=2n$	*B*-centred lattice	*B*
	$k+l=2n$	*A*-centred lattice	*A*
	$\left\{\begin{matrix} h+k=2n \\ h+l=2n \\ k+l=2n \end{matrix}\right\}$	Face centred lattice	*F*
	$\Rightarrow$ *h*, *k*, *l*, all even or all odd		
	$-h+k+l=3n$	Rhombohedral lattice indexed on hexagonal reference system	*R*
	$h+k+l=3n$	Hexagonal lattice indexed on rhombohedral reference system	*H*

* From M. J. Buerger, 'X-ray Crystallography', John Wiley & Sons, New York, 1942.

Table 4.10 MULTIPLICITY FACTORS FOR POWDER PHOTOGRAPHS

Laue or point-group symmetry	*hkl*	*hhl*	*0kl*	*0kk*	*hhh*	*00l*
			Cubic system			
$\bar{4}3m$, 43, $m3m$	48	24	24	12	8	6
23, $m3$	2 × 24	24	2 × 12	12	8	6

Laue or point-group symmetry	*hkil*	*hh$\bar{2}$hl*	*0k$\bar{k}$l*	*hki0*	*hh$\bar{2}$h0*	*0k$\bar{k}$0*	*000l*
			Hexagonal and rhombohedral systems				
$\bar{6}2m$, 6mm, 62, 6/mmm	24	12	12	12	6	6	2
6, $\bar{6}$, 6/m	2 × 12	12	12	2 × 6	6	6	2
3m, 32, $\bar{3}m$	2 × 12	12	2 × 6	12	6	6	2
3, $\bar{3}$	4 × 6	2 × 6	2 × 6	2 × 6	6	6	2

Laue or point-group symmetry	*hkl*	*hhl*	*0kl*	*hk0*	*hh0*	*0k0*	*00l*
			Tetragonal system				
$\bar{4}2m$, 4mm, 42, 4/mmm	16	8	8	8	4	4	2
4, $\bar{4}$, 4/m	2 × 8	8	8	2 × 4	4	4	2

Laue or point-group symmetry	*hkl*	*0kl*	*h0l*	*hk0*	*h00*	*0k0*	*00l*
			Orthorhombic system				
mm, 222, mmm	8	4	4	4	2	2	2

Laue or point-group symmetry	*hkl*	*h0l*	*0k0*
		Monoclinic system	
m, 2, 2/m	4	2	2

Laue or point-group symmetry	*hkl*
	Triclinic system
1, $\bar{1}$	2

Where the multiplicity is given, for example, as 2 × 6, this indicates two sets of reflections at the same angle but having different intensities.

Table 4.11 ANGULAR FACTORS

$\theta°$	$\sin^2\theta$	$\frac{1+\cos^2 2\theta}{\sin 2\theta}$	$\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}$	$\theta°$	$\sin^2\theta$	$\frac{1+\cos^2 2\theta}{\sin 2\theta}$	$\frac{1+\cos^2 2\theta}{\sin^2\theta\cos\theta}$
0	0.0000	∞	∞	45	0.500	1.000	2.828
1	0.0003	57.272	6563	47½	0.5436	1.011	2.744
½	0.0006	38.162	2916				
2	0.0011	28.601	1639.1	50	0.5868	1.046	2.731
2½	0.0019	22.860	1048				
3	0.0027	19.029	727.2	52½	0.6294	1.105	2.785
3½	0.0037	16.289	533.6	55	0.6710	1.189	2.902
4	0.0049	14.231	408.0	57½	0.7113	1.300	3.084
4½	0.0061	12.628	321.9				
5	0.0076	11.344	260.3	60	0.7500	1.443	3.333
6	0.0109	9.411	180.06				
7	0.0149	8.025	131.70	62½	0.7868	1.622	3.658
8	0.0193	6.980	100.31	65	0.8214	1.845	4.071
9	0.0243	6.163	78.80	67½	0.8536	2.121	4.592
10	0.0302	5.506	63.41	70	0.8830	2.469	5.255
12	0.0432	4.510	43.39	72	0.9045	2.815	5.920
14	0.0581	3.791	31.34	74	0.9240	3.244	6.749
16	0.0762	3.244	23.54	76	0.9415	3.791	7.814
18	0.0955	2.815	18.22	78	0.9568	4.510	9.221
20	0.1170	2.469	14.44	80	0.9698	5.506	11.182
22½	0.1465	2.121	11.086	81	0.9755	6.163	12.480
25	0.1786	1.845	8.730	82	0.9806	6.980	14.097
27½	0.2133	1.622	7.027	83	0.9851	8.025	16.17
				84	0.9891	9.411	18.93
30	0.2500	1.443	5.774	85	0.9924	11.344	22.78
				85½	0.9938	12.628	25.34
32½	0.2887	1.300	4.841	86	0.9951	14.231	28.53
35	0.3290	1.189	4.123	86½	0.9963	16.289	32.64
37½	0.3706	1.105	3.629	87	0.9973	19.029	38.11
				87½	0.9981	22.860	45.76
40	0.4131	1.046	3.255	88	0.9988	28.601	57.24
				88½	0.9993	38.162	76.35
42½	0.4564	1.011	2.994	89	0.9997	57.272	114.56
45	0.5000	1.000	2.828				
				90	1.000	∞	∞

4.3.2.2 Determination of retained austenite in steel

An important example of quantitative phase analysis by X-ray diffraction is the determination of retained austenite in steels. The method is based on the comparison of the integrated diffracted X-ray intensities of selected (*hkl*) reflections of the martensite and austenite phases. The necessary formulae and reference data are given below; for more details of the experimental methods the definitive paper by Durnin and Ridal[12] should be consulted.

The integrated intensity of a diffraction line is given by the equation:

$$I_{(hkl)} = n^2\, Vm\, (LP)\, e^{-2m}(Ff)^2 \tag{4.1}$$

in which $I_{(hkl)}$ = integrated intensity for a special (*hkl*) reflection; n = number of cells in cm^3; V = volume exposed to the X-ray beam; (LP) = Lorentz–Polarization factor; m = multiplicity of (*hkl*); e^{-2m} = Debye–Waller temperature factor; F = structure factor; and f = atomic factor.

For n^2V we may substitute V/v^2, in which v is the volume of the unit cell.

If the ratio between the integrated intensities of martensite and austenite is denoted by P:

$$P = \frac{I \text{ martensite } (\alpha)}{I \text{ austenite } (\gamma)} = \frac{V_\alpha\, v_\gamma^{\,2} m_\alpha (LP)_\alpha e_\alpha^{-2m} (F_\alpha f_\alpha)^2}{V_\gamma\, v_\alpha^{\,2} m_\gamma (LP)_\gamma e_\gamma^{-2m} (F_\gamma f_\gamma)^2} \tag{4.2}$$

Each factor is determined from the International Tables[5] and depends on the reflection used. A factor G is then determined for each combination of α and γ peaks used; hence:

$$P = \frac{V_\alpha}{V_\gamma} \times \frac{1}{G} \tag{4.3}$$

If α and γ are the only phases present:

$$V_\gamma = \frac{1}{1+GP} \tag{4.4}$$

Hence, measurement of the ratio (P) of two diffraction peaks and calculation of the factor G will give the volume fraction of austenite V_γ.

The factors involved in the calculation of G for two steels—16.8%Ni–Fe(0.35%C) and N C MV (a Ni–Cr–Mo–V steel with composition wt % 0.43C; 0.31Si; 0.57Mn; 0.009S; 0.005P; 1.69Ni; 1.36Cr; 1.08Mo; 0.24V; 0.11Cu), Mo, Co and Cr radiation and a selection of *hkl* peaks have been extracted from the 'International Tables for X-Ray Crystallography'[5] by Durnin and Ridal[12] and are presented in Table 4.12.

These factors may be used to calculate G for different radiations and peaks. The results are presented in Table 4.13.

When the alloy compositions are being investigated the factors which make up G must be determined from the International Tables.[5]

Accuracy obtainable using a diffractometer is in the region of 0.5% for the range 1.5–38 volume percentage of austenite. X-ray diffraction determination accuracy thus compares favourably with other techniques such as metallography, dilatometry and saturation magnetization intensity methods which are all inaccurate below 10% austenite content.

The main source of error in X-ray determination of retained austenite comes from overlapping carbide peaks. The carbides and their diffraction peaks most likely to cause problems are summarized in Table 4.14.

4.3.2.3 X-ray Residual Stress Measurements

Residual stresses can be divided into two general categories, macrostresses where the strain is uniform over relatively large distances and microstresses produced by non-uniform strain over short distances, typically a few hundred Å. Both types of stress can be measured by X-ray diffraction techniques.

The basis of stress measurement by X-ray diffraction is the accurate measurement of changes in interplaner d spacing caused by the residual stress. When macrostresses are present the lattice plane spacing in the crystals (grains) change from their stress-free values to new values corresponding with the residual stress and the elastic constants of the material. This produces a shift in the position of the corresponding diffraction, i.e. a change in Bragg angle θ. Microstresses however give rise to non-uniform variations in interplanar spacing which broaden the diffractions rather than cause a shift in their position. Small crystal size also give rise to broadening.

Measurement of Macro-residual stress[13–17]

The working equation used in most X-ray stress analysis is

$$\sigma\phi = \frac{d_\psi - d_\perp}{d_\perp} \times \frac{E}{1+\nu} \times \frac{1}{\sin^2\psi} \tag{1}$$

where σ_ψ is the surface stress lying in a direction common to the surface and the plane defined by the surface normal and the incident X-ray beam. E and ν are Young's modulus and Poisson's ratio respectively, d_ψ and $d_\perp$ are the interplanar spacings of planes with normals parallel to the surface normal and at an angle ψ to the surface normal. These angles are related to the direction of the incident X-ray beam, as shown in Fig. 4.1. Thus σ can be determined from two exposures, one with the incident beam inclined at θ to the surface to measure $d_\perp$ and the other at an angle ψ to the first to measure $d\psi$. This technique is known as the two-exposure technique.

Alternatively equation (1) can be rewritten as

$$d_\psi = d_\perp\left(\frac{1+\nu}{E}\right)\sigma\phi\sin^2\psi + d_\perp \tag{2}$$

Table 4.12 INTENSITY FACTORS FOR DIFFERENT RADIATIONS AND PEAKS[11]

Material	*Radiation*	*Factor*	*Peak* α200	α211	γ200	γ220	γ311
16.8%Ni–Fe	Mo	Bragg angle, θ	14.41	17.73	11.49	16.32	19.21
NCMV	Mo		14.40	17.70	11.49	16.32	19.21
16.8%Ni–Fe	Co		38.67	49.89	29.99	44.92	55.85
16.8%Ni–Fe	Cr		53.15	78.05	39.74	64.65	—
Both compositions	All	Multiplicity, m	6	24	6	12	24
Both	Mo	Lorentz and	29.46	18.84	47.56	22.55	15.78
	Co	polarization	3.44	2.73	5.79	2.83	2.96
	Cr	(LP)	2.81	9.26	3.29	4.01	–
16.8%Ni–Fe	Mo	Debye–Waller	0.910	0.869	0.943	0.889	0.847
NCMV	Mo	temp. e^{-2M}	0.910	0.869	0.943	0.889	0.848
16.8%Ni–Fe	Co		0.908	0.869	0.941	0.889	0.852
16.8%Ni–Fe	Cr		0.912	0.869	0.943	0.889	–
16.8%Ni–Fe	Mo	Atomic scattering,	15.1	13.4	17.0	14.0	12.8
NCMV	Mo	fo	14.7	13.1	16.6	13.7	12.5
16.8%Ni–Fe	Co		10.78	9.14	12.69	9.84	8.60
16.8%Ni–Fe	Cr		13.19	11.54	15.09	12.24	—
Both	All	Structure factor, F	2	2	4	4	4
Both	All	$1/V^2$ (V is volume of unit cell)	1.79×10^{-3} kx units		4.68×10^{-4} kx units		

Table 4.13 AUSTENITE DETERMINATION FACTOR *G* FOR DIFFERENT RADIATIONS AND PEAK COMBINATIONS[12]

Material	*Radiation*	*Peak combination* α200–γ200	α200–γ220	α200–γ311	α211–γ200	α211–γ220	α211–γ311
16.8%Ni–Fe	Mo	2.22	1.36	1.50	1.16	0.71	0.78
NCMV	Mo	2.23	1.38	1.51	1.15	0.72	0.78
16.8%Ni–Fe	Co	2.52	1.40	2.15	1.09	0.61	0.93
16.8%Ni–Fe	Cr	1.66	2.50	—	0.17	0.26	—

Table 4.14 INTERFERENCE OF ALLOY CARBIDE LINES WITH AUSTENITE AND MARTENSITE LINES[12]

Austenite and martensite 'd' spacings	Fe_3C	M_6C	V_4C_3	Mo_2C or W_2C	WC	$Cr_{23}C_6$	Cr_7C_3
(200)γ 1.80 Å	Clear	Clear	Clear	Clear	Clear	Strong overlap	Strong overlap
(200)α 1.43 Å	Clear	Strong overlap	Clear	Clear	Weak overlap	Weak overlap	Weak overlap
(220)γ 1.27 Å	Weak overlap	Strong overlap	Weak overlap	Strong overlap	Weak overlap	Medium overlap	Clear
(211)α 1.17 Å	Strong overlap	Clear	Clear	Weak overlap	Weak overlap	Medium overlap	Medium overlap
(311)γ 1.08 Å	Weak overlap	Medium overlap	Clear	Weak overlap	Clear	Strong overlap	Clear

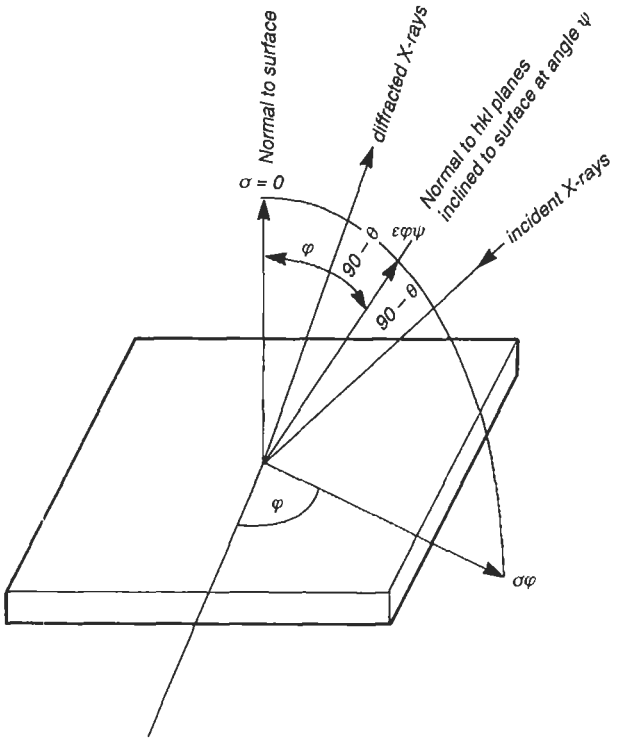


Figure 4.1

This shows that d_ψ is a linear function of $\sin^2\psi$. The intercept on the d axis gives $d_\perp$ and the slope $d_\perp((1+\nu)/E)\sigma\phi$. A positive slope corresponds to a tensile stress and a negative slope to compression. This technique takes advantage of measurements involving a number of d_ψ values.

The determination of interplanar spacings depends on the accurate measurement of the corresponding Bragg angle θ where

$$d_{hkl} = \frac{\lambda}{2\sin\theta_{hkl}}$$

Back reflection diffractions are used as the highest sensitivity to changes in interplanar spacing are obtained as θ tends to 90°. In practice the specimen is rotated through ψ between exposures (or the tube and detector together through the same angle on portable systems for measuring large samples).

Due to the limited penetration of commonly used X-ray wavelengths, typically 4 μM for chromium radiation to 11 μm for molybdenum in steel, only surface stresses are measured. Stresses at lower depths in the sample are determined by repeating measurements after removing (electropolishing) layers of known thickness. The measured values are subsequently corrected for changes in stress resulting from the removal of upper layers.

Residual stress in small components can be measured on a converted diffractometer by adding a specimen support table with three orthogonal adjustments to permit the surface of the component to be brought into the beam. Fully automated portable systems are available for determining residual stress in large components.

Typical accuracy for steel is ± 1.5–3.0×10^7 NM (± 1–2 ton in^{-2}).

MEASUREMENT OF MICROSTRESSES[18,19]

A worked surface gives rise to broadened diffractions due to a combination of microstresses and small crystallite size. An approximate method to separate the two effects is to assume that the breadth is the sum of the separate broadening from each effect.

The relationships between diffraction breadth β and average crystallite size ε and mean stress $\bar{\sigma}$ are:

1 Small crystallite alone $\beta_{s.c.} \simeq \dfrac{k\lambda}{\varepsilon_{hkl} \cos \Theta}$

where k is a constant $\simeq 1$ and ε_{hkl} is the linear dimension perpendicular to the measured hkl plane.

2 Microstresses alone $\beta_{M.S.} \simeq \dfrac{4\bar{\sigma} \tan \Theta}{E_{hkl}}$

where E_{hkl} is the elastic constant perpendicular to hkl.

When both effects are present, then

$$\beta = \beta_{s.c.} + \beta_{M.S.}$$
$$= \frac{\lambda}{\varepsilon_{hkl} \cos \Theta} + \frac{4\bar{\sigma} \tan \Theta}{E_{hkl}}$$

which can be rewritten in the form:

$$\frac{\beta \cos \Theta}{\lambda} = \frac{1}{\varepsilon_{hkl}} + \frac{4\bar{\sigma} \sin \Theta}{\lambda E_{hkl}}$$

If only these defects are present, then a plot of $\beta \cos \Theta / \lambda$ against $\sin \Theta$ should be a straight line, with intercept on the $\beta \cos \Theta / \lambda$ axis giving $1/\varepsilon_{hkl}$ and the slope $4\bar{\sigma}/\lambda E_{hkl}$.

For non-cubic materials, for example tetragonal and hexagonal, separate plots should be made for the hk0 and 00l results.

In the above formula, diffraction breadth is measured as either the breadth in radians at half the peak height (HPHW) or as the integral breadth which is the integrated intensity of the diffraction divided by the peak height. It corresponds to the width of a rectangle having the same area and height as the diffraction. The latter is particularly useful in analysing peaks with partially resolved $\alpha_1 \alpha_2$ doublets. The measured breadths include the instrumental breadth which is independent of any crystal defects. This can be measured for subsequent subtraction from the measured breadths by running a scan from a defect-free specimen.

4.3.2.4 Preferred orientation

Preferred orientation can be represented in two ways, either as a convential pole figure or as an inverse pole figure. A convential pole figure shows the distribution of a low-index pole—normal to a crystallographic plane, over the whole specimen. With a cubic metal, these are generally constructed for {100}, {110} and {111} planes while for hexagonal metals usually the basal (0001) plane is selected. A high density of poles shows the preferred direction of the pole with respect to the sample.

An inverse pole figure on the other hand shows how the grains are distributed with respect to a particular direction in the sample.[20] Inverse pole figures are usually constructed for the principal directions of the sample, for example the extrusion, radial, and tangential directions in extruded material. The method is rapid, and data for a single direction can be determined from a conventional diffractometer scan taken from a surface which is perpendicular to the required direction. The method is based on the fact that all diffractions recorded on a convential scan come from planes which are parallel to the surface and their intensities are related to the number of grains (volume of material) which has this orientation. The diffraction intensities are compared to those from a sample having random orientation. These can be either theoretical calculated values or values measured directly from a corresponding scan taken from a sample with random orientation. These relative intensities are called texture coefficients (TC) and are expressed mathematically as

$$TC_{(hkl)} = \frac{I_{(hkl)}/I^0_{(hkl)}}{\frac{1}{n}\sum_0^n I_{(hkl)}/I^0_{(hkl)}}$$

where

I = measured integrated intensity of a given hkl diffraction
I^0 = corresponding intensity for the same hkl diffraction from a random sample
n = total number of diffractions measured.

The TC_{hkl} values are proportional to the number of grains (volume of sample) which are oriented with an hkl plane parallel to the sample surface.

The values can be plotted on a partial sterographic projection and contour lines drawn through the plotted points to produce an 'Inverse Pole Figure' for that particular specimen direction. High values show the preferred grain orientation in the specimen direction.

4.3.2.5 Specimen preparation

Methods for preparing standard diffractometer specimens are discussed in references 1–4. The most common method is to pack loose powder into a flat cavity in an aluminium specimen holder, taking care not to introduce preferred orientation. Another method is to mix the powder into a slurry and smear some over a glass cover slip. Coarse powders which tend to slide out of the cavity during a scan can be mixed with petroleum jelly. The possibility of diffractions from the jelly or binder should always be considered when analysing the diffraction pattern.

A problem when analysing a small amount of material, is diffractions and scatter from the specimen holder. These effects are reduced by using a single crystal holder of a low element material which has been polished so the surface is just off a Bragg plane.

Most laboratories have developed procedures and specimen holders for non-standard applications. These have been surveyed by D. K. Smith and C. S. Barrett and the results published in 'Advances in X-ray Analysis'.[24] One application is the analysis of air-moisture reactive powders. A simple solution is to fill and seal the powder in thin walled glass quills inside a dry box. After removal from the glove box the quills are mounted in raft fashion across a recessed specimen holder. Sealed cells are also used to avoid handling delicate quills inside a glove box. One such method for lithium compounds was to load the powder inside a glove box into a recessed specimen holder and cover the powder with a flanged 0.001 in. thick aluminium foil dome. Petroleum jelly was lightly smeared round the flange to hold the dome on to the specimen holder and make a moisture seal.

Metal samples submitted for XRD analysis are generally metallurgically mounted and polished samples. Due to the limited penetration of the X-ray beam into the sample it is always advisable to first electropolish the surface. Useful electropolishes are listed in Chapter 10, Table 10.4. An electropolish frequently used in preparing specimens for retained austenite determinations is

7 vol% perchloric acid
69 vol% ethanol
10 vol% glycerol
14 vol% water

At a voltage of 23 V. Electrolyte maintained at temperature below 12°C.

EXTRACTION TECHNIQUES

Precipitates that are present at very low concentrations can be concentrated by dissolving away the matrix and collecting the residue. Typical solutions used for extraction are as follows.[25]

(i) Carbides and certain intermetallic compounds
 (a) Immersion overnight in 5 or 10% bromine in methanol,
 or
 (b) Electrolytically in 10% hydrochloric acid in methanol at a current density of 0.07 A cm^{-2}. Extraction for 4 h provides sufficient powder residue.

The intermetallic phases which can be extracted using these solutions are sigma phase, certain of the Laves phases, Fe_3Mo_2 etc.

(ii) Gamma prime, eta phase, M(CN)
 (a) Electrolytically in 10% phosphoric acid in water at a current density of 10 A dm^{-2}. Time of extraction 4 h. It is sometimes necessary to add a small amount of tartaric acid in order to prevent the formation of tantalum and tungsten hydroxides,
 or
 (b) Electrolytically in 1% citric acid plus 1% ammonium sulphate in water. Current density 2 A dm^{-2}, duration 4 h. For quantitative work this solution is preferred to the phosphoric acid electrolyte.

Certain of the Laves phases may also be extracted using either of these solutions.

(iii) Precipitates and intermetallic compounds in chromium
 Immersion overnight in 10% hydrochloride acid. This has been used to extract carbides and borides.

Precipitates can also be concentrated by heavily etching a surface to leave them proud of the surface as used to produce replicas in the early days of electron microscopy.[26]

Table 4.15 CRYSTAL GEOMETRY

System	d_{hkl} = *Interplanar spacing*	V = *Vol. of unit cell*
Cubic	$\frac{1}{d^2}=\frac{h^2+k^2+l^2}{a^2}$	$V=a^3$
Tetragonal	$\frac{1}{d^2}=\frac{h^2}{a^2}+\frac{k^2}{a^2}+\frac{l^2}{c^2}$	$V=a^2c$
Orthorhombic	$\frac{1}{d^2}=\frac{h^2}{a^2}+\frac{k^2}{b^2}+\frac{l^2}{c^2}$	$V=abc$
Rhombohedral*	$\frac{1}{d^2}=\frac{(h^2+k^2+l^2)\sin^2\alpha+2(hk+kl+hl)(\cos^2\alpha-\cos\alpha)}{a^2(1-3\cos^2\alpha+2\cos^3\alpha)}$	$V=a^3\sqrt{(1-3\cos^2\alpha+2\cos^3\alpha)}$
Hexagonal†	$\frac{1}{d^2}=\frac{4}{3}\left(\frac{h^2+hk+k^2}{a^2}\right)+\frac{l^2}{c^2}$	$V=\frac{\sqrt{3}}{2}a^2c=0.866\ a^2c$
Monoclinic	$\frac{1}{d^2}=\frac{h^2}{a^2\sin^2\beta}+\frac{k^2}{b^2}+\frac{l^2}{c^2\sin^2\beta}-\frac{2hl\cos\beta}{ac\sin^2\beta}$	$V=abc\sin\beta$
Triclinic	$\frac{1}{d^2}=\frac{1}{V^2}(s_{11}h^2+s_{22}k^2+s_{33}l^2+2s_{12}hk+2s_{23}kl+2s_{13}hl)$	$V=abc\sqrt{(1-\cos^2\alpha-\cos^2\beta-\cos^2\gamma+2\cos\alpha\cos\beta\cos\gamma)}$

System	ϕ = *angle between planes* $h_1k_1l_1$ *and* $h_2k_2l_2$
Cubic	$\cos\phi = \dfrac{h_1h_2+k_1k_2+l_1l_2}{\sqrt{[(h_1^2+k_1^2+l_1^2)(h_2^2+k_2^2+l_2^2)]}}$
Tetragonal	$\cos\phi = \dfrac{(h_1h_2/a^2)+(k_1k_2/a^2)+(l_1l_2/c^2)}{\sqrt{\{[(h_1^2/a^2)+(k_1^2/a^2)+(l_1^2/c^2)][(h_2^2/a^2)+(k_2^2/b^2)+(l_2^2/c^2)]\}}}$
Orthorhombic	$\cos\phi = \dfrac{(h_1h_2/a^2)+(k_1k_2/b^2)+(l_1l_2/c^2)}{\sqrt{\{[(h_1^2/a^2)+(k_1^2/b^2)+(l_1^2/c^2)][(h_2^2/a^2)+(k_2^2/b^2)+(l_2^2/c^2)]\}}}$
Rhombohedral*	$\cos\phi = \dfrac{(h_1h_2+k_1k_2+l_1l_2)\sin^2\alpha+(k_1l_2+k_2l_1+l_1h_2+l_2h_1+h_1k_2+h_2k_1)(\cos^2\alpha-\cos\alpha)}{\sqrt{\{[(h_1^2+k_1^2+l_1^2)\sin^2\alpha+2(h_1k_1+k_1l_1+h_1l_1)(\cos^2\alpha-\cos\alpha)][(h_2^2+k_2^2+l_2^2)\sin^2\alpha+2(h_2k_2+k_2l_2+h_2l_2)(\cos^2\alpha-\cos\alpha)]\}}}$
Hexagonal†	$\cos\phi = \dfrac{h_1h_2+k_1k_2+\frac{1}{2}(h_1k_2+h_2k_1)+\frac{3}{4}\cdot(a^2/c^2)\cdot l_1l_2}{\sqrt{\{[h_1^2+k_1^2+h_1k_1+\frac{3}{4}(a^2/c^2)l_1^2][h_2^2+k_2^2+h_2k_2+\frac{3}{4}(a^2/c^2)\cdot l_2^2]\}}}$
Monoclinic	$\cos\phi = \dfrac{(h_1h_2/a^2)+(k_1k_2\sin^2\beta/b^2)+(l_1l_2/c^2)-[(l_1h_2+l_2h_1)\cos\beta/ac]}{\sqrt{\{[(h_1^2/a^2)+(k_1^2\sin^2\beta/b^2)+(l_1^2/c^2)-(2h_1l_1\cos\beta/ac)][(h_2^2/a^2)+(k_2^2\sin^2\beta/b^2)+(l_2^2/c^2)-(2h_2l_2\cos\beta/ac)]\}}}$
Triclinic	$\cos\phi = \dfrac{d_{h_1k_1l_1}\cdot d_{h_2k_2l_2}}{V^2}[s_{11}h_1h_2+s_{22}k_1k_2+s_{33}l_1l_2+s_{23}(k_1l_2+k_2l_1)+s_{13}(l_1h_2+l_2h_1)+s_{12}(h_1k_2+h_2k_1)]$

where $s_{11}=b^2c^2\sin^2\alpha$ $\quad s_{12}=abc^2(\cos\alpha\cos\beta-\cos\gamma)$
$s_{22}=a^2c^2\sin^2\beta$ $\quad s_{23}=a^2bc(\cos\beta\cos\gamma-\cos\alpha)$
$s_{33}=a^2b^2\sin^2\gamma$ $\quad s_{13}=ab^2c(\cos\gamma\cos\alpha-\cos\beta)$

* Rhombohedral axes. † Hexagonal axes, co-ordinates *hkil* where $i=-(h+k)$.

4.3.2.6 Formulae and crystallographic data

Formulae for calculating interplanar d_{hkl} spacings from lattice parameters and data for calculating intensities together with other useful information on crystal symmetry are given in Tables 4.8, 4.9, 4.10, 4.11 and 4.15.

INTENSITIES

The relative intensities of diffractions recorded on a diffractometer scan are given by the formula

$$I \propto \left(\frac{1+\cos^2 2\theta}{\sin^2 \theta \cos \theta}\right)|F|^2 \,.\, \text{T.p.A}$$

where

$\left(\frac{1+\cos^2 2\theta}{\sin^2 \theta \cos \theta}\right)|F|^2 \,.\, \text{T.p.A}$ = Combined polarization Lorentz factor (Table 4.11)

F = structure factor involving the summation of scattering from all atoms in the unit cell

T = temperature factor, $e^{-\left(\frac{B \sin^2 \theta}{\lambda^2}\right)}$

p = multiplicity factor, Table 4.10

A = an absorption factor.

For a diffractometer specimen of effectively infinite thickness, $A = K/\mu$ where K is a constant and μ the linear absorption coefficient of the sample. A is therefore independent of θ. A criterion for this condition is that the thickness of the specimens is $> 3.2/\mu$.

Table 4.16 MEAN ATOMIC SCATTERING FACTORS*

$\frac{\text{Sin}\,\theta}{\lambda}$ Å^{-1}	*0.0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1.0*	*1.1*	*1.2*
H	1.000	0.811	0.481	0.251	0.130	0.071	0.040	0.024	0.015	0.010	0.007	0.005	0.0035
H^{-1}	2.000	1.064	0.519	0.255	0.130	0.070	0.040	0.024	0.015	0.010	0.007	0.005	0.0035
He	2.000	1.832	1.452	1.058	0.742	0.515	0.358	0.251	0.179	0.129	0.095	0.071	0.054
Li	3.000	2.215	1.741	1.512	1.269	1.032	0.823	0.650	0.513	0.404	0.320	0.255	0.205
Li^{+1}	2.000	1.935	1.760	1.521	1.265	1.025	0.818	0.647	0.510	0.403	0.319	0.254	0.203
Li^{-1}	4.000	2.176	1.743	1.514	1.269	1.033	0.826	0.654	0.516	0.408	0.323	0.257	0.205
Be	4.000	3.067	2.067	1.705	1.531	1.367	1.201	1.031	0.878	0.738	0.620	0.519	0.432
Be^{+1}	3.000	2.583	2.017	1.721	1.535	1.362	1.188	1.022	0.870	0.735	0.618	0.520	0.436
Be^{+2}	2.000	1.966	1.869	1.724	1.550	1.363	1.180	1.009	0.855	0.721	0.606	0.508	0.427
B	5.000	4.066	2.711	1.993	1.692	1.534	1.406	1.276	1.147	1.016	0.895	0.783	0.682
B^{+1}	4.000	3.471	2.551	1.962	1.688	1.536	1.410	1.283	1.154	1.028	0.908	0.798	0.698
B^{+2}	3.000	2.757	2.290	1.928	1.707	1.552	1.414	1.278	1.144	1.016	0.896	0.786	0.687
B^{+3}	2.000	1.979	1.919	1.824	1.703	1.566	1.420	1.274	1.132	0.999	0.877	0.767	0.669
C	6.000	5.126	3.581	2.502	1.950	1.685	1.536	1.426	1.322	1.218	1.114	1.012	
C^{+2}	4.000	3.686	2.992	2.338	1.910	1.672	1.533	1.429	1.332	1.233	1.131	1.030	
C^{+3}	3.000	2.842	2.487	2.133	1.874	1.697	1.564	1.447	1.335	1.225	1.116	1.012	0.913
C^{+4}	2.000	1.986	1.945	1.880	1.794	1.692	1.579	1.459	1.338	1.219	1.104	0.994	0.893
N	7.000	6.203	4.600	3.241	2.397	1.944	1.698	1.550	1.444	1.350	1.263	1.175	1.083
N^{-3}	4.000	3.772	3.227	2.635	2.172	1.869	1.682	1.558	1.461	1.373	1.287	1.199	1.112
N^{+4}	3.000	2.890	2.619	2.306	2.038	1.837	1.690	1.573	1.472	1.375	1.281	1.188	1.097
N^{-1}	8.000	6.688	4.631	3.186	2.364	1.929	1.694	1.551	1.446	1.352	1.263	1.170	
O	8.000	7.250	5.634	4.094	3.010	2.338	1.944	1.714	1.566	1.462	1.374	1.296	1.220
O^{+1}	7.000	6.493	5.298	4.017	3.016	2.356	1.956	1.717	1.567	1.461	1.374	1.296	
O^{+2}	6.000	5.647	4.776	3.771	2.924	2.327	1.948	1.716	1.568	1.463	1.378	1.301	
O^{+3}	5.000	4.760	4.151	3.410	2.745	2.246	1.913	1.701	1.562	1.463	1.382	1.308	
O^{-1}	9.000	7.836	5.756	4.068	2.968	2.313	1.934	1.710	1.566	1.46	1.373	1.294	
F	9.000	8.293	6.691	5.044	3.760	2.878	2.312	1.958	1.735	1.587	1.481	1.496	
F^{-1}	10.00	9.108	7.126	5.188	3.786	2.885	2.323	1.972	1.747	1.596	1.486	1.399	1.322
Ne	10.00	9.363	7.824	6.987	4.617	3.536	2.794	2.300	1.976	1.760	1.612	1.504	1.419
Na	11.0	9.76	8.34	6.89	5.47	4.29	3.40	2.76	2.31	2.00	1.78	1.63	1.52

* Condensed from 'International Tables for X-ray Crystallography', Kynoch Press, Birmingham, England, 1962.

Table 4.16 MEAN ATOMIC SCATTERING FACTORS*—*continued*

$\frac{\sin\theta}{\lambda}$ Å^{-1}	*0.0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1.0*	*1.1*	*1.2*
Na^+	10.00	9.551	8.390	6.925	5.510	4.328	3.424	2.771	2.314	2.001	1.785	1.634	1.524
Mg	12.00	10.50	8.75	7.46	6.20	5.01	4.06	3.30	2.72	2.30	2.01	1.81	1.65
Mg^{+2}	10.00	9.66	8.75	7.51	6.20	4.99	4.03	3.28	2.71	2.30	2.01	1.81	1.65
Al	13.00	11.23	9.16	7.88	6.77	5.69	4.71	3.88	3.21	2.71	2.32	2.05	1.83
Al^{+1}	12.00	10.94	9.22	7.90	6.77	5.70	4.71	3.88	3.22	2.70	2.32	2.04	
Al^{+2}	11.00	10.40	9.17	7.65	6.79	5.70	4.71	3.88	3.22	2.71	2.33	2.05	1.84
Al^{+3}	10.00	9.74	9.01	7.98	6.82	5.69	4.69	3.86	3.20	2.70	2.32	2.04	1.84
Si	14.00	12.16	9.67	8.22	7.20	6.24	5.31	4.47	3.75	3.16	2.69	2.35	2.07
Si^{+3}	11.00	10.53	9.48	8.34	7.27	6.25	5.30	4.44	3.73	3.14	2.67	2.34	
Si^{-4}	10.00	9.79	9.20	8.33	7.31	6.26	5.28	4.42	3.71	3.13	2.68	2.33	2.06
P	15.00	13.17	10.34	8.59	7.54	6.67	5.83	5.02	4.28	3.64	3.11	2.69	2.35
S	16.00	14.33	11.21	8.99	7.83	7.05	6.31	5.56	4.82	4.15	3.56	3.07	2.66
S^{-1}	17.00	15.00	11.36	8.95	7.79	7.05	6.32	5.57	4.83	4.16	3.57	3.08	2.67
S^{-2}	18.00	(15.16)	(10.74)	(8.66)	(7.89)	(7.22)	(6.47)	(5.69)	(4.93)	(4.23)	(3.62)	(3.13)	(2.71)
Cl	17.00	15.33	12.00	9.44	8.07	7.29	6.64	5.96	5.27	4.60	4.00	3.47	3.02
Cl^{-1}	18.00	16.02	12.22	9.40	8.03	7.28	6.64	5.97	5.27	4.61	4.00	3.47	3.03
A	18.00	16.30	12.93	10.20	8.54	7.56	6.86	6.23	5.61	5.01	4.43	3.90	3.43
K	19.00	16.73	13.73	10.97	9.05	7.87	7.11	6.51	5.95	5.39	4.84	4.32	3.83
K^{+1}	18.00	16.68	13.76	10.96	9.04	7.86	7.11	6.51	5.94				
Ca	20.00	17.33	14.32	11.71	9.64	8.26	7.38	6.75	6.21	5.70	5.19	4.69	4.21
Ca^{+1}	19.00	17.21	14.35	11.70	9.63	8.26	7.38	6.75	6.21	5.70	5.19	4.68	
Ca^{+2}	18.00	16.93	14.40	11.70	9.61	8.25	7.38	6.75	6.22	5.70	5.18	4.68	
Sc	21.00	18.72	15.38	12.39	10.12	8.60	7.64	6.98	6.45	5.96	5.48	5.00	4.53
Sc^{+1}	20.00	18.50	15.43	12.43	10.13	8.61	7.64	6.98	6.45	5.96	5.48	5.00	5.53
Sc^{+2}	19.00	17.88	15.27	12.44	10.18	8.64	7.65	6.98	6.45	5.96	5.48	5.01	4.54
Sc^{+3}	18.00	17.11	14.92	12.38	10.22	8.68	7.76	6.98	6.44	5.96	5.49	5.02	4.56
Ti	22.00	19.96	16.41	13.68	11.53	9.88	8.57	7.52	6.65	5.95	5.36	4.86	4.43
Ti^{+1}	21.00	19.61	16.55	13.64	11.53	9.98	8.56	7.52					
Ti^{+2}	20.00	18.99	16.52	13.75	11.50	9.86	8.58	7.52					
Ti^{+3}	19.00	18.24	16.27	13.82	11.58	9.84	8.55	7.53					
V	23.00	20.90	17.23	14.39	12.15	10.43	9.05	7.95	7.05	6.31	5.69	5.15	4.70
V^{+1}	22.00	20.56	17.37	14.36	12.15	10.44	9.05	7.95					
V^{+2}	21.00	19.94	17.35	14.46	12.12	10.41	9.07	7.96					
V^{+3}	20.00	19.19	17.11	14.54	12.19	10.38	9.04	7.97					
Cr	24.00	21.84	18.05	15.11	12.78	10.98	9.55	8.39	7.44	6.67	6.01	5.45	4.97
Cr^{+1}	23.00	21.50	18.20	15.07	12.78	10.99	9.54	8.40					
Cr^{+2}	22.00	20.89	18.18	15.18	12.75	10.97	9.56	8.40					
Cr^{+3}	21.00	20.15	17.96	15.26	12.82	10.94	9.53	8.41					
Mn	25.00	22.77	18.88	15.84	13.41	11.54	10.04	8.84	7.85	7.03	6.34	5.75	5.25
Mn^{+1}	24.00	22.44	19.02	15.79	13.42	11.55	10.04	8.84					
Mn^{+2}	23.00	21.84	19.01	15.90	13.38	11.53	10.06	8.84					
Mn^{+3}	22.00	21.10	18.80	15.99	13.45	11.50	10.03	8.85					
Mn^{+4}	21.00	20.30	18.42	15.97	13.54	11.53	10.00	8.82					
Fe	26.00	23.71	19.71	16.56	14.05	12.11	10.54	9.29	8.25	7.39	6.67	6.06	5.53
Fe^{+1}	25.00	23.39	19.85	16.52	14.05	12.12	10.54	9.29					
Fe^{+2}	24.00	22.79	19.85	16.62	14.02	12.09	10.56	9.29					
Fe^{+3}	23.00	22.06	19.65	16.71	14.08	12.06	10.54	9.30					
Fe^{+4}	22.00	21.26	19.28	16.71	14.18	12.09	10.50	9.28					
Co	27.00	24.65	20.54	17.29	14.69	12.67	11.05	9.74	8.66	7.77	7.01	6.37	5.82
Co^{+1}	26.00	24.33	20.68	17.25	14.70	12.68	11.04	9.74					
Co^{+2}	25.00	23.74	20.69	17.35	14.66	12.66	11.07	9.74					
Co^{+3}	24.00	23.01	20.50	17.44	14.72	12.63	11.04	9.76					
Ni	28.00	25.60	21.37	18.03	15.34	13.25	11.56	10.20	9.08	8.14	7.35	6.68	6.11
Ni^{+1}	27.00	25.28	21.52	17.98	15.34	13.25	11.55	10.20					
Ni^{+2}	26.00	24.69	21.53	18.08	15.30	13.24	11.58	10.19					
Ni^{+3}	25.00	23.97	21.35	18.18	15.36	13.20	11.56	10.21					
Cu	29.00	26.54	22.21	18.76	15.98	13.82	12.07	10.66	9.46	8.52	7.70	7.00	6.40
Cu^{+1}	28.00	26.22	22.35	18.71	15.99	13.83	12.07	10.66					
Cu^{+2}	27.00	25.64	22.37	18.81	15.95	13.81	12.09	10.65					
Cu^{+3}	26.00	24.93	22.20	18.91	16.00	13.77	12.07	10.68					

* Condensed from 'International Tables for X-ray Crystallography', Kynoch Press, Birmingham, England, 1962.

Table 4.16 MEAN ATOMIC SCATTERING FACTORS*—*continued*

$\frac{\sin\theta}{\lambda}$ Å^{-1}	*0.0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1.0*	*1.1*	*1.2*
Zn	30.00	27.48	23.05	19.50	16.64	14.40	12.59	11.12	9.91	8.90	8.05	7.32	6.70
Zn^{+2}	28.00	26.59	23.32	19.55	16.60	14.40	12.61	11.12					
Ga	31.00	28.43	23.89	20.35	17.29	14.98	13.11	11.59	10.33	9.29	8.40	7.64	6.99
Ga^{+1}	30.00	28.12	24.03	20.19	17.30	14.99	13.10	11.60					
Ga^{+2}	28.00	26.84	23.90	20.39	17.30	14.93	13.11	11.61					
Ge	32.00	29.37	24.73	20.99	17.95	15.57	13.63	12.06	10.76	9.68	8.76	7.97	7.29
Ge^{+2}	30.00	28.50	24.91	21.03	17.92	15.57	13.65	12.06					
Ge^{+4}	28.00	27.02	24.45	21.18	18.05	15.53	13.60	12.07					
As	33.00	30.32	25.58	21.74	18.61	16.16	14.16	12.54	11.19	10.07	9.11	8.30	7.60
As^{+1}	32.00	30.02	25.72	21.68	18.63	16.16	14.16	12.54					
As^{+2}	31.00	29.45	25.76	21.77	18.58	16.16	14.18	12.53					
As^{+3}	30.00	28.75	25.62	21.88	18.61	16.11	14.17	12.53					
Se	34.00	31.26	26.42	22.49	19.28	16.75	14.69	13.02	11.62	10.46	9.47	8.63	7.91
Br	35.00	32.21	27.27	23.24	19.95	17.35	15.22	13.50	12.06	10.86	9.84	8.97	8.21
Kr	36.00	33.16	28.12	24.00	20.62	17.95	15.76	13.98	12.50	11.26	10.21	9.31	8.53
Rb	37.00	34.11	28.97	24.75	21.29	18.55	16.30	14.47	12.94	11.66	10.58	9.65	8.84
Rb^{+1}	36.00	33.82	29.11	24.70	21.31	18.55	16.30	14.48					
Sr	38.00	35.06	29.83	25.51	21.96	19.15	16.84	14.96	13.39	12.07	10.95	9.99	9.16
Y	39.00	36.01	30.68	26.28	22.64	19.76	17.39	15.46	13.84	12.48	11.32	10.34	9.48
Zr	40.00	36.96	31.54	27.04	23.32	20.37	17.94	15.95	14.29	12.89	11.70	10.68	9.80
Zr^{+4}	36.00	34.72	31.39	27.25	23.39	20.31	17.92	15.97					
Nb	41.00	37.91	32.40	27.81	24.01	20.98	18.49	16.45	14.74	13.31	12.08	11.04	10.13
Mo	42.00	38.86	33.25	28.57	24.69	21.60	19.04	16.95	15.20	13.73	12.46	11.39	10.45
Mo^{+1}	41.00	38.59	33.39	28.51	24.72	21.59	19.04	16.96					
Tc	43.00	39.81	34.12	29.34	25.38	22.21	19.60	17.46	15.65	14.15	12.85	11.74	10.78
Ru	44.00	40.76	34.98	30.12	26.07	22.83	20.16	17.96	16.12	14.57	13.24	12.10	11.11
Rh	45.00	41.72	35.84	30.89	26.76	23.46	20.72	18.47	16.58	14.99	13.63	12.46	11.45
Pd	46.00	42.67	36.70	31.67	27.46	24.08	21.28	18.98	17.05	15.42	14.02	12.82	11.78
Ag	47.00	43.63	37.57	32.44	28.16	24.71	21.85	19.50	17.52	15.85	14.42	13.19	12.12
Ag^{+1}	46.00	43.37	37.71	32.38	28.18	24.70	21.85	19.50					
Cd	48.00	44.58	38.44	33.22	28.85	25.34	22.42	20.02	17.99	16.28	14.81	13.56	12.46
In	49.00	45.53	39.31	34.00	29.56	25.97	22.99	20.53	18.46	16.71	15.21	13.93	12.80
Sn	50.00	46.49	40.17	34.78	30.26	26.60	23.56	21.05	18.93	17.15	15.61	14.30	13.15
Sb	51.00	47.45	41.05	35.57	30.96	22.74	24.14	21.58	19.41	17.59	16.02	14.67	13.49
Te	52.00	48.40	41.92	36.35	31.67	27.87	24.71	22.10	19.89	18.03	16.42	15.05	13.84
I	53.00	49.36	42.79	37.14	32.38	28.51	25.29	22.63	20.37	18.47	16.83	15.42	14.19
Xe	54.00	50.32	43.66	37.93	33.09	29.16	25.87	23.16	20.86	18.92	17.24	15.80	14.54
Cs	55.00	51.27	44.54	38.72	33.80	29.80	26.46	23.69	21.34	19.36	17.65	16.18	14.90
Ba	56.00	52.23	45.41	39.51	34.51	30.44	27.04	24.22	21.83	19.81	18.07	16.57	15.25
La	57.00	53.19	46.29	40.30	35.23	31.09	27.63	24.76	22.32	20.26	18.48	16.95	15.61
Ce	58.00	54.15	47.16	41.09	35.94	31.74	28.22	25.30	22.81	20.71	18.90	17.34	15.97
Pr	59.00	55.11	48.04	41.89	36.66	32.39	28.81	25.84	23.31	21.17	19.32	17.72	16.33
Nd	60.00	56.07	48.92	42.69	37.38	33.04	29.40	26.38	23.80	21.62	19.74	18.11	16.69
Pm	61.00	57.02	49.80	43.48	38.10	33.69	29.99	26.92	24.30	22.08	20.16	18.51	17.05
Sm	62.00	57.98	50.68	44.28	38.82	34.35	30.59	27.46	24.80	22.54	20.58	18.90	17.42
Eu	63.00	58.94	51.56	45.08	39.55	35.01	31.19	28.01	25.30	23.00	21.01	19.29	17.79
Gd	64.00	59.91	52.45	45.88	40.27	35.66	31.79	28.56	25.80	23.46	21.44	19.69	18.16
Tb	65.00	60.87	53.33	46.68	41.00	36.33	32.39	29.11	26.31	23.93	21.87	20.09	18.53
Dy	66.00	61.83	54.21	47.49	41.73	36.99	32.99	29.66	26.81	24.39	22.30	20.49	18.90
Ho	67.00	62.79	55.10	48.29	42.46	37.65	33.59	30.21	27.32	24.86	22.73	20.89	19.27
Er	68.00	63.75	55.98	49.10	43.19	38.31	34.20	30.76	27.83	25.33	23.17	21.29	19.65
Tm	69.00	64.71	56.87	49.90	43.92	38.98	34.81	31.32	28.34	25.80	23.60	21.70	20.03
Yb	70.00	65.67	57.75	50.71	44.66	39.65	35.42	31.88	28.85	26.28	24.04	22.11	20.40
Lu	71.00	66.64	58.64	51.52	45.39	40.32	36.03	32.44	29.37	26.75	24.48	22.51	20.78
Hf	72.00	67.60	59.53	52.33	46.13	40.99	36.64	33.00	29.88	27.23	24.92	22.92	21.17
Ta	73.00	68.56	60.42	53.14	46.86	41.66	37.25	33.56	30.40	27.70	25.36	23.33	21.55
W	74.00	69.52	61.31	53.95	47.60	42.33	37.87	34.12	30.92	28.18	25.80	23.74	21.93
Re	75.00	70.49	62.20	54.76	48.34	43.01	38.48	34.69	31.44	28.66	26.25	24.16	22.32
Os	76.00	71.45	63.09	55.58	49.08	43.68	39.10	35.26	31.96	29.14	26.70	24.57	22.70
Ir	77.00	72.42	63.98	56.39	49.83	44.36	39.72	35.82	32.48	29.63	27.14	24.99	23.09

* Condensed from 'International Tables for X-ray Crystallography', Kynoch Press, Birmingham, England, 1962.

Table 4.16 MEAN ATOMIC SCATTERING FACTORS*—*continued*

$\frac{\sin\theta}{\lambda}$ Å^{-1}	*0.0*	*0.1*	*0.2*	*0.3*	*0.4*	*0.5*	*0.6*	*0.7*	*0.8*	*0.9*	*1.0*	*1.1*	*1.2*
Pt	78.00	73.38	64.87	57.21	50.57	45.04	40.34	36.39	33.01	30.11	27.59	25.41	23.48
Au	79.00	74.35	65.77	58.02	51.31	45.72	40.96	36.96	33.53	30.60	28.04	25.83	23.87
Au^{+1}	78.00	74.14	65.88	57.96	51.35	45.70	40.97	36.97					
Hg	80.00	75.31	66.66	58.84	52.06	46.40	41.59	37.54	34.06	31.08	28.50	26.25	24.27
Hg^{+2}	78.00	74.65	66.90	58.79	52.05	46.41	41.59	37.53					
Tl	81.00	76.27	67.55	59.66	52.81	47.08	42.22	38.12	34.60	31.59	28.68	26.68	24.67
Tl^{+1}	80.00	76.07	67.67	59.59	52.84	47.06	42.23	38.12					
Tl^{+3}	78.00	75.03	67.82	59.71	52.76	47.08	42.24	38.10					
Pb	82.00	77.24	68.45	60.48	53.56	47.77	42.85	36.69	35.13	32.08	29.42	27.11	25.07
Pb^{+3}	79.00	76.00	68.71	60.53	53.50	47.76	42.87	38.68					
Bi	83.00	78.20	69.34	61.30	54.30	48.45	43.47	39.27	35.66	32.57	29.87	27.53	25.46
Po	84.00	79.17	70.24	62.12	55.05	49.14	44.10	39.85	36.19	33.06	30.33	27.96	25.86
At	85.00	80.13	71.13	62.94	55.80	49.82	44.73	40.43	36.73	33.55	30.79	28.38	26.26
Rn	86.00	81.10	72.03	63.76	56.56	50.51	45.36	41.01	37.26	34.05	31.25	28.81	26.66
Fe	87.00	82.07	72.93	64.58	57.31	51.20	45.99	41.59	37.80	34.55	31.71	29.24	27.06
Ra	88.00	83.03	73.82	65.41	58.06	51.89	46.63	42.17	38.34	35.04	32.17	29.67	27.46
Ac	89.00	84.00	74.72	66.23	58.82	52.58	47.26	42.75	38.88	35.54	32.64	30.10	27.87
Th	90.00	84.97	75.62	67.06	59.57	53.27	47.90	43.34	39.42	36.05	33.10	30.54	28.27
Pa	91.00	85.93	76.52	67.88	60.33	53.97	48.53	43.93	39.96	36.55	33.57	30.97	26.68
U	92.00	86.90	77.42	68.71	61.09	54.66	49.17	44.51	40.50	37.05	34.04	31.41	29.09

*Condensed from 'International Tables of X-ray Crystallography', Kynoch Press, Birmingham, England, 1962.
Note: For elements of atomic number 22 or more factors are from Thomas–Fermi–Dirac Statistical Model.

Table 4.17 MASS ABSORPTION COEFFICIENT μ/ρ, CORRECTED FOR SCATTERING*

		Radiation											
Absorber		Ag $K\alpha=0.5609$ $K\beta=0.4970$	Pd 0.5869 0.5205	Rh 0.6147 0.5456	Mo 0.7107 0.6323	Zn 1.4364 1.2952	Cu 1.5418 1.3922	Ni 1.6591 1.5001	Co 1.7902 1.6207	Fe 1.9373 1.7565	Mn 2.1031 1.9102	Cr 2.2909 2.0848	Ti 2.7496 2.5138
H	1	0.371 0.366	0.373 0.368	0.375 0.370	0.381 0.376	0.425 0.414	0.434 0.421	0.446 0.430	0.462 0.442	0.482 0.458	0.509 0.479	0.545 0.506	0.658 0.595
He	2	0.195 0.190	0.197 0.192	0.199 0.194	0.207 0.200	0.348 0.306	0.384 0.334	0.430 0.369	0.490 0.414	0.569 0.474	0.673 0.554	0.813 0.661	1.261 1.010
Li	3	0.187 0.178	0.191 0.181	0.196 0.185	0.217 0.200	0.611 0.493	0.716 0.572	0.850 0.673	1.025 0.804	1.254 0.978	1.556 1.209	1.960 1.520	3.260 2.533
Be	4	0.229 0.208	0.239 0.215	0.251 0.224	0.307 0.258	1.245 0.958	1.498 1.149	1.823 1.393	2.245 1.711	2.796 2.130	3.526 2.688	4.474 3.439	7.636 5.884
B	5	0.279 0.245	0.295 0.257	0.314 0.270	0.393 0.327	1.965 1.490	2.386 1.806	2.927 2.213	3.628 2.742	4.545 3.438	5.757 4.365	7.378 5.614	12.58 9.674
C	6	0.400 0.333	0.432 0.356	0.464 0.383	0.625 0.495	3.764 2.815	4.603 3.446	5.680 4.257	7.075 5.310	8.899 6.697	11.31 8.542	13 4.53 11.02	24.83 19.08
N	7	0.544 0.433	0.597 0.471	0.658 0.515	0.916 0.700	6.132 4.557	7.524 5.603	9.311 6.950	11.62 8.698	14.64 11.00	18.63 14.05	23.95 18.16	40.96 31.47
O	8	0.740 0.570	0.821 0.628	0.916 0.696	1.313 0.980	9.337 6.917	11.48 8.53	14.22 10.60	17.76 13.28	22.39 16.80	28.48 21.48	36.61 27.76	62.52 48.07
F	9	0.943 0.710	1.056 0.790	1.187 0.884	1.737 1.276	12.79 9.459	15.72 11.67	19.48 14.51	24.34 18.19	30.67 23.02	39.01 29.43	50.10 38.02	85.38 65.72
Ne	10	1.308 0.965	1.471 1.082	1.662 1.218	2.463 1.792	18.53 13.96	22.79 16.91	28.23 21.03	35.26 26.37	44.41 33.36	56.43 42.62	72.39 55.01	123.0 94.82
Na	11	1.644 1.198	1.857 1.350	2.106 1.528	3.147 2.275	23.96 18.05	29.45 21.87	36.46 27.19	45.50 34.05	57.24 43.05	72.65 54.95	93.07 70.83	157.5 121.7
Mg	12	2.171 1.568	2.458 1.774	2.794 2.014	4.202 3.024	32.15 24.26	39.49 29.35	48.86 36.47	69.92 45.65	76.55 57.65	97.01 73.50	124.1 94.60	209.0 161.9
Al	13	2.671 1.917	3.030 2.174	3.450 2.474	5.208 3.736	39.90 30.14	48.98 36.55	60.53 45.24	75.37 56.57	94.57 71.35	119.6 90.82	152.7 116.7	255.9 198.7
Si	14	3.330 2.379	3.783 2.703	4.312 3.082	6.525 4.672	50.06 37.84	61.42 45.73	75.87 56.75	94.41 70.92	118.4 89.40	149.4 113.7	190.8 146.0	318.8 247.9

P	15	3.992	4.539	5.179	7.852	60.04	73.58	90.78	112.8	141.1	178.0	226.4	375.9
		2.842	3.234	3.692	5.614	45.47	54.88	68.02	84.90	106.8	135.6	173.7	293.3
S	16	5.014	5.705	6.513	10.43	84.24	92.00	113.3	140.5	175.5	220.8	280.0	461.5
		3.561	4.056	4.824	7.403	57.03	68.74	85.08	106.0	133.2	168.7	215.5	361.5
Cl	17	5.796	6.599	7.536	11.44	86.38	105.6	129.8	160.6	200.1	251.1	317.4	518.5
		4.109	4.684	5.356	8.172	65.68	79.03	97.70	121.5	152.3	192.5	245.2	408.1
A	18	6.486	7.385	8.435	12.81	95.83	116.9	143.5	177.2	220.2	275.3	346.7	560.9
		4.592	5.238	5.992	9.148	73.06	87.75	108.3	134.4	168.1	211.8	268.9	443.7
K	19	8.238	9.382	10.72	16.26	120.4	146.6	179.6	221.3	274.0	341.5	428.1	684.6
		5.830	6.651	7.611	11.62	92.09	110.3	135.9	168.3	210.0	263.8	333.6	545.0
Ca	20	9.872	11.24	12.83	19.48	142.5	173.1	211.5	259.7	320.6	398.0	496.6	783.4
		6.984	7.970	9.120	13.93	109.3	130.7	160.6	198.4	246.7	308.9	389.0	628.2
Sc	21	10.66	12.14	13.86	21.00	151.7	183.8	223.9	274.1	337.1	416.5	516.8	802.4
		7.543	8.608	9.851	15.03	116.7	139.2	170.7	210.3	260.6	325.0	407.3	649.0
Ti	22	12.08	13.75	15.70	23.65	169.0	204.3	248.0	302.5	370.5	455.3	561.2	98.45
		8.548	9.754	11.16	17.02	130.6	155.3	189.9	233.2	288.0	357.4	445.5	75.84
V	23	13.54	15.41	17.58	26.56	185.8	224.0	271.0	329.2	401.0	489.9	68.38	116.2
		9.585	10.94	12.51	19.06	144.2	171.0	208.4	255.1	313.6	387.3	479.7(*k*)	89.57
Cr	24	15.67	17.83	20.34	30.67	210.7	253.1	305.0	368.7	446.7	55.67	70.08	118.8
		11.11	12.67	14.49	22.03	164.3	194.2	235.9	287.5	351.8	431.9	53.30	91.70
Mn	25	17.39	19.78	22.54	33.94	228.3	273.3	327.8	394.1	57.20	72.59	93.00	157.4
		12.34	14.08	16.08	24.42	179.1	210.7	255.0	309.5	376.6(*k*)	54.90	70.78	121.6
Fe	26	19.91	22.63	25.79	38.74	254.9	303.7	362.5	53.48	67.25	85.29	109.2	184.4
		14.14	16.11	18.41	27.92	200.2	235.6	283.9	342.8(*k*)	50.61	64.56	83.16	142.6
Co	27	21.83	24.79	28.23	42.31	271.5	322.0	48.18	60.17	75.48	95.66	122.4	206.1
		15.52	17.68	20.19	30.55	215.7	251.5	301.6(*k*)	45.02	56.85	72.47	93.29	159.6
Ni	28	25.18	28.59	32.53	48.62	303.5	45.99	56.15	69.88	89.03	112.7	144.1	242.1
		17.93	20.42	23.30	35.19	243.0	281.7(*k*)	42.49	53.17	67.17	85.49	110.0	187.7
Cu	29	26.55	30.12	34.24	51.05	40.41	49.61	61.32	76.35	95.81	121.2	154.7	259.3
		18.93	21.54	24.58	37.03	30.53	36.91	45.82	57.31	72.28	92.01	118.2	201.3
Zn	30	29.30	33.22	37.74	56.09	45.73	56.10	69.30	86.23	108.1	136.7	174.2	291.1
		20.92	23.80	27.13	40.78	34.57	41.77	51.83	64.78	81.65	103.9	133.3	226.4
Ga	31	31.04	35.16	39.90	59.12	49.49	60.69	74.92	93.15	116.7	147.3	187.6	312.5
		22.20	25.24	28.76	43.11	37.44	45.22	56.08	70.05	88.22	112.1	143.8	243.5

Table 4.17 MASS ABSORPTION COEFFICIENT μ/ρ, CORRECTED FOR SCATTERING—*continued*

		Radiation											
Absorber		Ag $K\alpha=0.5609$ $K\beta=0.4970$	Pd 0.5869 0.5205	Rh 0.6147 0.5456	Mo 0.7107 0.6323	Zn 1.4364 1.2952	Cu 1.5418 1.3922	Ni 1.6591 1.5001	Co 1.7902 1.6207	Fe 1.9373 1.7565	Mn 2.1031 1.9102	Cr 2.2909 2.0848	Ti 2.7496 2.5138
Ge	32	33.49 24.00	37.90 27.27	42.98 31.04	63.43 46.39	54.70 41.34	66.91 49.90	82.55 61.85	102.6 77.20	128.3 97.14	161.9 123.3	205.9 158.0	341.8 266.7
As	33	36.29 26.07	41.04 29.60	46.49 33.66	68.36 50.14	60.44 45.81	74.03 55.26	91.25 68.44	113.3 85.36	141.6 107.3	178.4 136.1	226.6 174.1	374.8 293.0
Se	34	38.31 27.59	43.28 31.29	48.97 35.56	71.69 52.78	65.14 49.52	79.72 49.57	98.19 73.73	121.8 91.88	152.1 115.4	191.3 146.2	242.6 186.8	399.8 313.3
Br	35	41.95 30.29	47.33 34.32	53.50 38.96	77.97 57.61	72.75 55.26	88.97 66.55	109.5 82.31	135.7 102.5	169.2 128.6	212.7 162.7	269.2 207.6	441.8 346.9
Kr	36	44.18 31.98	49.79 36.20	56.19 41.05	81.49 60.46	78.20 59.47	95.57 71.56	117.5 88.44	145.4 110.0	181.2 137.9	227.4 174.3	287.4 222.0	469.4 369.5
Rb	37	47.51 34.49	53.47 39.01	60.26 44.18	83.32 64.78	85.88 65.39	104.9 78.61	128.8 97.1	159.2 120.6	198.2 151.0	248.2 190.6	313.2 242.4	509.2 401.8
Sr	38	50.74 36.95	57.03 41.74	64.18 47.22	92.04 68.92	93.51 71.30	114.1 85.63	140.0 105.6	172.9 131.2	214.8 164.0	268.7 206.7	338.3 262.4	547.3 433.0
Y	39	54.50 39.83	61.16 44.93	68.71 50.76	97.92 73.72	102.5 78.24	124.9 93.87	153.1 115.7	188.8 143.5	234.3 179.2	292.5 225.5	367.6 285.8	591.3 469.2
Zr	40	57.66 42.29	64.61 47.66	72.45 53.76	14.94 77.63(*k*)	110.7 84.64	134.8 101.5	165.1 124.9	203.3 154.8	251.9 193.0	313.9 242.5	393.6 306.7	629.3 501.0
Nb	41	61.23 45.09	68.49 50.73	76.65 57.14	16.23 82.02(*k*)	119.5 97.71	145.4 109.6	177.8 134.8	218.7 166.9	270.5 207.7	336.5 260.5	420.9 328.8	668.6 534.1
Mo	42	63.87 47.23	71.30 53.07	79.63 59.67	19.90 14.22	145.9 111.9	177.2 133.8	216.5 164.4	265.8 203.1	328.3 252.6	407.5 316.2	508.4 398.3	802.1 643.2
Tc	43	66.43 49.36	84.01 55.37	14.22 62.14(*k*)	21.57 15.42	157.0 120.7	190.6 144.1	232.5 176.9	285.1 218.2	351.3 271.0	435.1 338.5	541.5 425.4	847.8 682.6
Ru	44	69.16 51.65	76.88 57.83	15.07 64.78(*k*)	22.85 16.35	165.2 127.2	200.2 151.7	243.9 185.9	298.6 229.1	367.2 283.9	453.7 354.0	563.0 443.7	874.3 707.0
Rh	45	72.82 54.68	14.34 61.10(*k*)	16.37 11.63	24.81 17.75	178.0 137.3	215.5 163.5	262.1 200.2	320.3 246.3	393.1 304.7	484.5 379.1	599.2 473.9	922.2 749.4

Pd	46	13.32	15.17	17.32	26.22	186.7	225.7	284.0	334.2	409.2	502.9	619.9	944.7
		56.28(k)	10.75	12.31	18.78	144.3	171.6	209.8	257.6	318.1	394.8	492.1	777.1
Ag	47	14.42	16.41	18.74	28.35	200.2	241.6	292.9	356.5	435.5	533.7	655.4	988.1
		10.20	11.64	13.32	20.31	155.0	184.1	224.7	275.5	339.5	420.4	522.4	812.1
Cd	48	15.11	17.20	19.63	29.68	207.8	250.5	303.1	368.1	448.4	547.8	670.1	998.4
		10.70	12.21	13.97	21.28	161.3	191.2	233.1	285.2	350.7	433.1	536.4	825.9
In	49	16.14	18.36	20.95	31.65	219.6	264.2	319.1	386.7	469.9	572.0	696.8	102.5
		11.42	13.03	14.91	22.71	170.9	202.2	246.1	300.6	368.7	454.0	560.4	853.9
Sn	50	16.96	19.29	22.01	33.21	228.2	274.0	330.2	399.2	483.5	586.3	710.6	103.0
		12.00	13.69	15.66	23.85	178.0	210.2	255.3	311.2	380.9	467.5	574.6	864.9
Sb	51	17.94	20.41	23.29	35.10	238.9	286.4	344.5	415.3	501.5	605.9	730.8	975.4
		12.71	14.50	26.58	25.23	186.8	220.3	267.1	324.9	396.5	485.1	594.0	883.5(l_{I})
Te	52	18.54	21.09	24.04	36.21	243.8	291.8	350.1	420.9	506.5	609.2	730.6	513.1(l_{II})
		13.14	14.99	17.14	26.04	191.2	225.0	272.3	330.5	401.2	490.3	597.6	727.3(l_{I})
I	53	20.15	22.91	26.12	39.30	261.7	312.5	374.0	448.3	537.4	643.4	766.8	223.0(l_{III})
		14.29	16.29	18.63	28.29	205.9	241.7	291.9	353.4	428.7	520.6	631.5	447.8(l_{II})
Xe	54	21.03	23.91	27.24	40.94	269.5	321.2	383.3	458.0	546.8	651.2	642.2(l_{I})	243.9
		14.93	17.01	19.44	29.50	212.7	249.1	300.2	362.5	438.3	530.2	639.6(L)	470.1(l_{II})
Cs	55	22.40	25.46	29.00	43.54	283.1	336.6	400.6	476.9	567.0	671.3	669.7(l_{I})	271.1
		15.90	18.13	20.71	31.39	224.2	261.9	314.9	379.1	456.9	550.1	659.8(L)	212.4
Ba	56	23.31	26.48	30.16	45.21	290.2	344.3	408.5	484.6	573.3	565.9(l_{I})	417.0(l_{II})	293.3
		16.56	18.87	21.56	33.64	230.7	268.9	322.5	387.1	464.7	556.8(L)	555.1(l_{I})	230.0
La	57	24.76	28.12	32.01	47.94	303.7	359.2	424.8	501.8	590.7	359.0(l_{II})	197.7	322.9
		17.60	20.06	22.93	34.64	242.2	281.6	336.8	402.9	481.8	574.2(L)	576.6(l_{I})	254.1
Ce	58	26.34	29.91	34.03	50.89	317.9	375.0	442.0	519.8	512.8(l_{II})	383.1(l_{II})	218.0	354.5
		18.74	21.35	24.37	36.82	254.5	295.1	352.0	419.7	499.6(L)	497.1(l_{I})	374.9(l_{II})	279.7
Pr	59	28.04	31.82	36.21	54.07	332.7	391.1	459.3	537.5	333.4(l_{III})	190.6	240.1	388.3
		19.96	22.73	25.95	39.16	267.5	309.1	367.6	436.4	517.3(L)	518.3(l_{I})	186.2	307.2
Nd	60	29.29	33.24	37.80	56.37	341.4	400.1	467.9	461.4(l_{I})	349.4(l_{II})	205.7	258.4	415.7
		20.87	23.76	27.11	40.87	275.7	317.7	376.6	445.5(L)	442.4(l_{I})	337.4(i_{II})	200.9	329.9
Pm	61	30.91	35.05	39.85	59.34	353.4	412.6	480.4	304.1(i_{II})	169.4	211.3	265.2	425.3
		22.04	25.09	28.61	43.08	286.8	329.3	388.9	458.0(L)	458.5(l_{I})	357.0(l_{II})	206.4	338.1
Sm	62	31.99	36.28	41.22	61.28	358.6	417.2	411.6(l_{I})	314.9(l_{II})	174.2	217.1	272.2	435.2
		22.84	25.98	29.63	44.54	292.5	334.6	393.8(L)	390.9(l_{I})	300.5(l_{II})	167.7	212.1	346.4

Table 4.17 MASS ABSORPTION COEFFICIENT μ/ρ, CORRECTED FOR SCATTERING*—*continued*

		Radiation											
Absorber		Ag $K\alpha = 0.5609$ $K\beta = 0.4970$	Pd 0.5869 0.5205	Rh 0.6147 0.5456	Mo 0.7107 0.6323	Zn 1.4364 1.2952	Cu 1.5418 1.3922	Ni 1.6591 1.5001	Co 1.7902 1.6207	Fe 1.9373 1.7565	Mn 2.1031 1.9102	Cr 2.2909 2.0848	Ti 2.7496 2.5138
Eu	63	33.72 24.09	38.22 27.41	43.41 31.24	64.43 46.90	370.1 303.6	326.5(l_I) 345.9(L)	276.0(l_{II}) 340.7(l_I)	153.1 404.7(l_I)	189.4 317.7(i_{II})	235.6 182.4	294.7 230.2	468.1 374.0
Gd	64	34.66 24.79	39.26 28.18	44.57 32.11	66.04 48.14	371.8 306.9	367.1(l_I) 348.1(L)	284.1(i_{II}) 345.1(l_{II})	162.3 268.1(l_{II})	200.4 154.2	248.7 193.0	310.3 243.1	489.6 392.6
Tb	65	36.38 26.04	41.20 29.60	46.75 33.72	69.14 50.48	324.1(l_I) 316.6(L)	249.3(l_{II}) 357.6(L)	142.9 356.7(l_I)	175.1 281.9(l_{II})	215.8 166.5	267.3 208.0	332.6 261.3	520.7 518.1
Dy	66	37.83 27.11	42.82 30.80	48.56 35.06	71.69 52.41	217.7(l_{II}) 323.2(L)	259.4(i_{II}) 309.8(l_I)	152.7 242.5(i_{II})	186.9 143.4	229.9 177.8	284.1 221.7	352.5 277.8	547.4 442.6
Ho	67	39.83 28.57	45.06 32.45	51.07 36.93	75.26 55.11	230.1(l_{II}) 333.8(L)	135.7 212.9(l_{II})	165.0 256.0(l_{II})	201.7 155.1	247.5 191.9	305.0 238.7	377.3 298.4	580.7 471.9
Er	68	41.73 30.03	47.19 34.02	53.46 38.70	78.62 57.66	241.4(l_{II}) 292.2(l_I)	139.0 223.6(l_{II})	168.9 129.1	206.1 158.7	252.7 196.1	311.0 243.7	383.9 304.2	587.9 479.1
Tm	69	43.04 30.93	48.63 35.11	55.06 39.91	80.81 59.37	117.6 198.6(i_{II})	142.2 230.9(l_{II})	172.7 132.2	210.6 162.3	257.8 200.4	316.9 248.7	390.6 310.1	595.2 486.3
Yb	70	44.49 32.02	50.25 36.33	56.87 41.28	83.28 61.30	120.6 206.2(l_{II})	145.6 110.8	176.6 135.4	215.2 166.1	263.2 204.9	323.0 254.0	397.3 316.1	602.2 493.5
Lu	71	46.41 33.45	52.40 37.93	59.26 43.08	86.60 63.85	123.5 215.4(l_{II})	149.0 113.5	180.6 138.6	219.8 169.9	268.5 209.4	329.1 259.2	404.1 322.1	609.2 500.7
Hf	72	53.58 38.66	60.48 43.82	68.34 49.75	99.63 73.60	124.9 302.4(l_{II})	151.0 114.8	183.3 140.3	223.6 172.4	273.8 212.8	336.5 264.1	414.7 329.2	632.0 516.3
Ta	73	55.53 40.13	62.63 45.46	70.74 51.58	102.9 76.16	133.3 103.3	160.9 122.6	195.1 149.7	237.4 183.5	290.0 226.1	355.4 279.9	436.4 347.9	658.0 540.7
W	74	57.57 41.66	64.88 47.16	73.24 53.49	106.3 78.81	142.1 110.3	171.3 130.8	207.3 159.4	251.7 195.1	306.7 239.9	374.6 296.2	458.3 366.9	682.9 564.8
Re	75	59.37 43.03	66.87 48.69	75.42 55.19	109.1 81.12	151.4 117.7	182.0 139.3	219.8 169.5	266.3 207.0	323.6 253.9	394.0 312.7	479.9 385.7	706.0 588.1
Os	76	60.97 44.25	68.63 50.05	77.36 56.69	111.6 83.17	158.5 123.6	190.5 146.1	229.6 177.5	277.7 216.4	336.5 264.9	408.4 325.3	495.4 400.2	719.6 603.7

Ir	77	63.40	71.32	80.33	115.6	168.4	201.9	242.9	292.8	353.7	427.3	515.6	736.1
		46.09	52.10	58.98	86.32	131.7	155.3	188.3	229.1	279.6	342.1	419.0	623.5
Pt	78	65.68	73.93	83.09	119.2	178.5	213.7	256.3	308.2	370.9	451.9	535.0	749.6
		47.82	54.02	61.12	89.24	140.0	164.8	199.4	242.0	294.5	359.0	437.6	641.7
Au	79	67.84	76.19	85.67	122.5	188.3	224.9	269.2	322.7	386.9	463.2	552.3	758.7
		49.48	55.87	63.16	91.96	148.1	173.9	210.0	254.3	308.6	374.8	454.7	656.8
Hg	80	69.90	78.46	88.15	125.7	198.8	237.1	283.2	338.6	404.8	482.7	572.6	773.1
		51.07	57.62	65.11	94.57	156.8	183.8	221.6	267.7	324.0	392.3	474.0	675.9
Tl	81	71.77	80.49	90.37	128.4	206.7	245.7	292.5	348.2	414.0	490.3	576.1	
		52.52	59.23	66.87	96.90	163.6	191.2	229.9	276.8	333.6	401.7	481.9	
Pb	82	73.74	82.63	92.67	131.2	215.4	255.6	303.1	359.5	425.6	500.5	583.1	
		54.07	60.93	68.75	99.31	171.1	199.6	239.2	287.2	344.7	413.0	492.2	
Bi	83	76.60	85.78	96.13	135.7	226.8	268.3	317.4	375.0	441.5	516.2	596.0	
		56.26	63.37	71.44	103.0	180.0	210.3	251.5	301.0	359.9	429.2	508.1	
Po	84	79.42	88.86	99.50	139.9	237.7	280.3	330.3	388.5	454.6	527.3	602.0	
		58.44	65.77	74.11	106.5	190.3	220.6	263.1	313.7	373.4	442.5	519.5	
At	85	81.40	90.97	101.7	122.1(l_I)	249.2	293.1	344.4	403.4	469.6	540.7	611.0	
		60.05	67.53	76.00	108.8(L)	200.2	231.6	275.5	327.4	388.1	457.5	533.2	
Rn	86	82.38	91.97	102.7	122.5(l_I)	249.0	291.9	341.5	397.8	459.8	524.3		
		60.91	68.44	76.96	109.8(L)	201.1	231.7	274.7	325.1	383.4	448.6		
Fr	87	83.36	92.98	103.7	91.18(l_{II})	258.8	302.2	351.8	407.2	466.7	526.0		
		61.77	69.35	77.92	110.8(L)	210.1	241.1	284.8	335.5	393.1	456.2		
Ra	88	85.43	95.17	106.0	95.03(l_{II})	266.6	309.9	358.7	412.0	467.3			
		63.47	91.20	79.91	113.1(L)	217.8	248.9	292.7	342.7	398.6			
Ac	89	86.25	95.95	106.7	97.50(l_{II})	273.6	314.6	364.3	415.4				
		64.30	72.04	80.75	102.1(l_I)	224.7	255.8	299.5	348.8				
Th	90	88.04	97.82	97.75(l_I)	100.3(l_{II})	278.6	320.5	366.1					
		65.81	73.66	82.48(L)	75.07(l_{II})	230.6	261.1	304.0					
Pa	91	90.63	88.60(i_I)	72.19(i_{II})	103.2(l_{II})	290.1	332.8	378.6					
		67.91	75.95(L)	84.95(L)	77.4(l_{II})	240.2	272.2	316.0					
U	92	93.18	89.92(l_I)	74.20(l_{II})	105.9(i_{II})	294.9	336.7	380.7					
		69.94	78.17(L)	87.38(L)	79.70(l_{II})	246.7	275.2	320.3					

* Reproduced by permission from the *International Tables for X-ray Crystallography*.

4.4 X-ray results

4.4.1 Metal Working

Table 4.18 GLIDE ELEMENTS AND FRACTURE PLANES OF METAL CRYSTALS

		Low temperatures		*Elevated temperatures*		*Most closely packed*		
Structure	*Metal*	*Glide plane*	*Glide direction*	*Glide plane*	*Glide direction*	*Lattice plane*	*Lattice direction*	*Fracture plane*
Cubic, face centred	Al, Cu, Ag, Au, Pb			Approximately 450 °C (100)	[101]	*1*(111) *2*(100) *3*(110)	*1*[10$\bar{1}$] *2*[100] *3*[112]	— — —
	Ni, Cu-Au, α-Cu-Zn, α-Cu-Al, Al-Cu, Al-Zn, Au-Ag	(111)	[10$\bar{1}$]	—	—	—	—	—
Cubic, body centred	α-Fe	(100)	[11$\bar{1}$]	—	—	*1*(101) *2*(100) *3*(111)	*1*[111] *2*[100] *3*[110]	(001)
		(112)	[11$\bar{1}$]	—	—			
		(123)	[11$\bar{1}$]	—	—			
	W	(112)	[11$\bar{1}$]	—	—			
	Mo	(112)	[11$\bar{1}$]	(110)	[1$\bar{1}$1]	—	—	—
	K	(123)	[11$\bar{1}$]	(123)	[11$\bar{1}$]	—	—	—
	Na	(112)	[11$\bar{1}$]	(110)	[11$\bar{1}$]	—	—	—
		—	—	(123)	[11$\bar{1}$]	—	—	—
	β-Cu-Zn	(110)	[11$\bar{1}$]	—	—	—	—	—
		(112)(?)	—	—	—	—	—	—
	α-Fe-Si, 5% Si	(110)	—	—	—	—	—	
Hexagonal, close packed	Mg, Zn, Cd, Be, Zn-Cd, Zn-Sn	(0001)	[11$\bar{2}$0]	Approximately 225 °C (10$\bar{1}$1) *or* (10$\bar{1}$2)	[11$\bar{2}$0]	(0001)	[11$\bar{2}$0]	(0001), (10$\bar{1}$1), (10$\bar{1}$2), (10$\bar{1}$0)
Tetragonal	β-Sn (white)	(110)	[001]	Approximately 150 °C		*1*(100)	*1*[001]	—
		(100)	[001]	(110)	[$\bar{1}$11]	*2*(110)	*2*[111]	—
		(101)	—	—	—	*3*(101)	*3*[100]	—
		(121)	[10$\bar{1}$]	—	—	—	*4*[101]	—
Rhombo-hedral	As	—	—	—	—	*1*($\bar{1}$10)	*1*[$\bar{1}$01]	(111), (1$\bar{1}$0)
	Sb	(111)	[10$\bar{1}$] and	—	—	*2*(11$\bar{1}$)	—	(111), (110), (11$\bar{1}$)
	Bi	(11$\bar{1}$)	[101]	—	—	—	—	(111), (11$\bar{1}$), (110)
	Hg	(100) and complex	—	—	—	—	—	—
Hexagonal	Te	(10$\bar{1}$0)	[11$\bar{2}$0]	—	—	(10$\bar{1}$1)	—	(10$\bar{1}$0)

4.4.2 Crystal Structure

Crystal structural data for free elements are given in Table 4.25. The coordination number, that is the number of nearest neighbours in contrast with an atom, is listed in column 4 and the distances in column 5. In complex structures, such as α Mn where the coordination is not exact, no symbol is used and the range of distances between near neighbours is given.

Table 4.19 PRINCIPAL TWINNING ELEMENTS FOR METALS

Crystal structure	*Twinning plane, K_1*	*Twinning direction, η_1*	*Second undistorted plane, K_2*	*Direction η_2*	*Shear*
B.c.c.	{112}	⟨11$\bar{1}$⟩	{11$\bar{2}$}	⟨111⟩	0.707
F.c.c.	{111}	⟨11$\bar{2}$⟩	{11$\bar{1}$}	⟨112⟩	0.707
Rhombohedral (As, Sb, Bi)	{110}	⟨00$\bar{1}$⟩	{001}	⟨110⟩	
All c.p.h.	{10$\bar{1}$2}	⟨$\bar{1}$011⟩	{$\bar{1}$012}	⟨10$\bar{1}$1⟩	
Some c.p.h.	{11$\bar{2}$1}	⟨11$\bar{2}$6⟩	{0001}	⟨11$\bar{2}$0⟩	
	{11$\bar{2}$2}	⟨11$\bar{2}$3⟩	{11$\bar{2}$4}	⟨22$\bar{4}$3⟩	
	{11$\bar{2}$3}	—	—	—	
Hg	{135}	⟨$\bar{1}$21⟩	{$\bar{1}$11}	⟨0$\bar{1}$1⟩	
Diamond cubic (Ge)	{111}	⟨11$\bar{2}$⟩	{11$\bar{1}$}	⟨112⟩	0.707
Tetragonal (In, β-Sn)	{301}	⟨$\bar{1}$03⟩	{$\bar{1}$01}	⟨101⟩	
	{101}	⟨10$\bar{1}$⟩	{$\bar{1}$01}	⟨101⟩	
Orthorhombic α-U	{130}	⟨3$\bar{1}$0⟩	{1$\bar{1}$0}	⟨110⟩	0.299
	{172}	⟨312⟩	{112}		0.228
	{112}			⟨312⟩	0.228
	{121}			⟨311⟩	0.329
	{176}	⟨512⟩	{1$\bar{1}$1}	⟨123⟩	0.214

From C. S. Barrett and T. B. Maggalski, 'Structure of Metals'.[2]

A co-ordination symbol x in column 4 indicates that each atom has x equidistant nearest neighbours, at a distance from it (in kX-units) specified in column 5. The symbol x, y indicates that a given atom has x equidistant nearest neighbours, and y equidistant neighbours lying a small distance further away. These distances are given in column 5. In complex structures, such as α-Mn, where the co-ordination is not exact, no symbol is used, and the range of distances between near neighbours is given in column 5.

The Goldschmidt atomic radii given in column 6 are the radii appropriate to 12-fold co-ordination In the case of the f.c.c. and c.p.h. metals the radius given is one-half of the measured interatomic distance, or of the mean of the two distances for the hexagonal packing. In the case of the b.c.c. metals, where the measured interatomic distances are for 8-fold co-ordination, a numerical correction has been applied. In some cases, where the pure element crystallizes in a structure having a low degree of co-ordination, or where the co-ordination is not exact, it is possible to find some compound or solid solution in which the element exists in 12-fold co-ordination, and hence to calculate its appropriate radius. In a few cases no correction for co-ordination has been attempted, and here the figures, given in parentheses, are one-half of the smallest interatomic distances. It should be emphasized that the Goldschmidt radii must not be regarded as constants subject only to correction for co-ordination and applicable to all alloy systems: they may vary with the solvent or with the degree of ionization, and they depend to some extent on the filling of the Brillouin zones.

Ionic radii vary largely with the valency, and to a smaller extent with co-ordination. The values given in column 8 are appropriate to 6-fold co-ordination, and have been derived either by direct measurement or by methods similar to those outlined for the atomic radii. All are based, ultimately, on the value of 1.32 Å obtained for O^{2+} ions by Wasastjerna,[28] using refractivity measurements. Ionic radii are also affected by the charge on neighbouring ions: thus in CaF_2 the fluorine ion is 3% smaller than in KF, where the metal ion carries a smaller charge. It is not possible to give a simple correction factor, applicable to all ions: the effect is specific and is especially marked in structures of low co-ordination. Figures in arbitrary units indicating the power of one ion to bring about distortion in a neighbour (its 'polarizing power'), and indicating the susceptibility of an ion to such distortion (its 'polarizability') are given in columns 9 and 10, respectively.

The crystal structures of alloys and compounds are listed in Chapter 6, Table 6.1. Other sources of data are references 7 and Pearson[23] which is particularly valuable as the variation of lattice parameters with composition as well as structure is given. Structures are generally referred to standard types which are listed in Pearson and in Table 6.2 in Chapter 6. Further information on pure crystallography can be obtained from International Tables For X-ray Crystallography.[5]

Table 4.20 ROLLING TEXTURES IN METALS AND ALLOYS

Metal or alloy	*Texture* 1	2	3
Face-centred cubic			
Cu	(110)/[1$\bar{1}$2]		
Cu	(123)/[1$\bar{2}$1]		
Cu*	(123)/[1$\bar{2}$1]		
Cu 70%-Zn 30%	(110)/[$\bar{1}$12]		
Cu 70%-Zn 30%*	(110)/[$\bar{1}$12]		
Cu + 12 at. % Al	(123)/[1$\bar{2}$1]	(110)/[$\bar{1}$12]	
Cu + 1.5 at. % Al	(110)/[$\bar{1}$12]		
Cu + 3 at. % Au	(123)/[1$\bar{2}$1]	(110)/[$\bar{1}$12]	
Cu + 29.6 at. % Ni	(123)/[1$\bar{2}$1]		
Cu + 49 at. % Ni	(123)/[1$\bar{2}$1[	(110)/[$\bar{1}$12]	
Ni	(123)/[1$\bar{2}$1]		
Au	(123)/[1$\bar{2}$1]		
Au + 10 at. % Cu	(110)/[$\bar{1}$12]		
Al	(123)/[1$\bar{2}$1]		
Al	(110)/[$\bar{1}$12]		
Al + 2 at. % Cu	(110)/[1$\bar{1}$2]		
Al + 1.25 at. % Si	(123)/[1$\bar{2}$1]		
Al + 0.7 at. % Mg	(110)/[1$\bar{1}$2]	(123)/[1$\bar{2}$1]	
Ag	(110)/[1$\bar{1}$2]		
Pb + 2 wt % Sb	(110)/[011]		
Body-centred cubic			
α-Fe	(100)/[011]		
α-Fe	(100)/[011]	(112)/[11$\bar{0}$]	(111)/[11$\bar{2}$]
Mo	(100)/[011]		
W	(100)/[011]		
V	(100)/[011]	(112)/[1$\bar{1}$0]	(111)/[11$\bar{2}$]
Fe + 4.16 wt % Si	(100)/[011]	Scatter increases with Si content	

Metal or alloy	*Texture* 1	2	3
Body-centred cubic (continued)			
Fe + 35 wt % Co	(100)/[011]		
Fe + 35 wt % Ni	(100)/[011]		
β-Brass	(100)/[011]	(112)/[1$\bar{1}$0]	(111)/[11$\bar{2}$] (111)/[1$\bar{1}$0]
Hexagonal close-packed			
Be, $\frac{c}{a} = 1.5847$	(0001)/[10$\bar{1}$0]		
Ti, $\frac{c}{a} = 1.5873$	(0001) tilted approx. 25–30° round RD out of rolling plane; ; [10$\bar{1}$0] parallel RD (0001)/[11$\bar{2}$0]		
Zr, $\frac{c}{a} = 1.5893$	(0001) tilted 30–40° round RD out of rolling plane; [10$\bar{1}$0] parallel RD		
Mg, $\frac{c}{a} = 1.6235$	(0001) parallel rolling plane		
β-Co, $\frac{c}{a} = 1.623$	(0001) parallel rolling plane		
Zn, $\frac{c}{a} = 1.8563$ Cd, $\frac{c}{a} = 1.8859$	(0001) tilted 20° round transverse direction out of rolling plane		
Mg + Al (< 4% by wt)	(0001)/[10$\bar{1}$0]		
Mg + 2% Mn Mg + 0.4% Co	(0001) tilted ~15° out of rolling plane around transverse direction		
Rhombohedral			
α-U	(102)/[010]	(012)/[02$\bar{1}$]	

* Straight-reverse rolling treatment.

From A. Taylor 'X-ray Metallography', John Wiley and Sons Inc.

Table 4.21 FIBRE TEXTURES OF DRAWN AND EXTRUDED WIRE*

Metal	*Parallel to drawing direction* 1	2	*Parallel to extrusion direction*
Face-centred cubic			
Al, Cu			[110]
Ni, Pd, Ag, Au, Pb, Cu + 0.47% Ag, Cu + 0.45% Sb, Cu + 1.0% As, Cu + 0.009% Bi	[111]	[100]	
Cu-Ni (< 32% Ni), Cu-Al (< 2.16% Al), Cu-Zn (< 2.35% Zn)			[110], [113] and [110]
Cu-Al (> 4.4% Al), Cu-Zn (> 4.8% Zn)	[111]		
α-Brass, α-Bronze, Ni + 20% Cr, Ni-Fe, austenite, 18/8 and 12/12 Cr-Ni steel	[111]	[100]	
Body-centred cubic			
α-Fe, β-Brass			[111] and [100]
Na, α-Fe, W, V, Nb, Ta	[110]		
Hexagonal close-packed			
Mg, $\frac{c}{a} = 1.6235$	[0001] ⊥ [11$\bar{2}$0] [10$\bar{1}$0]		[0001]
Zn, $\frac{c}{a} = 1.8563$	[0001] approx. 72° to drawing direction		
Ti, $\frac{c}{a} = 1.5873$	[10$\bar{1}$0]	[10$\bar{1}$1]	
Zr, $\frac{c}{a} = 1.5893$	[0001] ⊥		
Se, $\frac{c}{a} = 1.131$			[11$\bar{2}$0]

* After E. Schmid.
From A. Taylor, 'X-ray Metallography'.

Table 4.22 TEXTURES IN ELECTRODEPOSITS*

Metal	*Fibre textures*
Ni	[100]; [100] + [110]; [112]
Cu	[110]; [100]
Ag	[111] + [100]; [111]; [110]
Pb	[112]
Au	[110]
Fe	[111]; [112]
Co	[110]
Cr	[100] + [111] (f.c.c.); [0001] (hexagonal)
Sn	[111]; [001]
Cd	[11$\bar{2}$2]
Bi	[211]; [100]

* From C. S. Barrett, 'Structure of Metals', McGraw-Hill, New York, 1943.

Table 4.23 TEXTURES IN EVAPORATED AND SPUTTERED FILMS*

	Metal deposited	*Texture*	*Technique*
Face centred cubic	Ag	[111]; [100]; [110]	Evaporated
	Al	[111]; [100]; [110]	Evaporated
	Au	[110]; [111]	Evaporated
	Pt	[100]; [111]	Sputtered
	Pd, Cu, Ni	[111]	Evaporated
Body centred cubic	Fe	[111]	Evaporated
	Mo	[110]	Evaporated
Hexagonal	Cd, Zn	[0001]	Evaporated
Rhombohedral	Bi	[111]; [110]	Evaporated

* From C. S. Barrett, 'Structure of Metals', McGraw-Hill, New York, 1943.[2]

Table 4.24 TEXTURES OF CAST METALS*

Structure	*Metal*	*Normal to cold surface*
Body centred cubic	Fe–Si (4.3% Si)	[100]
	β-Brass	[100]
Face centred cubic	Al, Cu, Ag, Au, Pb, α-Brass	[100]
Hexagonal close packed†	Cd ($c/a = 1.885$)	Columnar grains, [001]; (100) ‖ to surface Chilled surface, [001]
	Zn ($c/a = 1.856$)	Columnar grains, [001]; (100) ‖ to surface Chilled surface, [001]
	Mg ($c/a = 1.624$)	Columnar grains, [100]; (205) ‖ to surface and (001) 37° from it
Rhombohedral	Bi	[111]
Tetragonal	β-Sn	[110]

* From C. S. Barrett, 'Structure of Metals', McGraw-Hill, New York, 1943.

† Three indices system; equivalent indices in four indices systems are as follows: (001) = (0001) = basal plane; [100] = [2$\bar{1}\bar{1}$0] = diagonal axis of type I = close packed row of atoms in basal plane; [100] normal to surface = (120) parallel to surface.

The density of a material is calculated from crystallographic data with the relation

$$p_c = \frac{n\bar{A}}{VN}$$

where n is the number of atoms contained in the unit cell of volume V, A is Avogadro's number and $\bar{A}$ is the mean atomic weight of the atoms. $\bar{A}$ is computed from the atomic percentages p_1, p_2, etc, of the elements forming the alloy and their atomic weights A_1, A_2, etc, using the formula

$$\bar{A} = \frac{p_1 A}{100} + \frac{P_2 A_2}{100} + \cdots$$

Table 4.25 ATOMIC AND IONIC RADII

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
			As element				*In ionic crystals*		
Atomic number	*Symbol*	*Type of structure*	*Co-ordination No.*	*Inter-atomic distances*	*Gold-schmidt at. radii*	*State of ionization*	*Gold-schmidt ionic radii*	*Polarizing power*	*Polarizability*
1	H	c.p.h	6, 6	—	0.46	H	1.54	0.62	—
2	He	—	—	—	—	—	—	—	—
3	Li	b.c.c.	8	3.03	1.57	Li^+	0.78	1.64	0.075
4	Be	c.p.h.	6, 6	2.22; 2.28	1.13	Be^{2+}	0.34	17.30	0.028
5	B	—	—	—	0.97	B^{3+}	0.2	—	0.014
6	C	d.	4	1.54	0.77				
		hex.	3	1.42	—	C^{4+}	<0.2	—	—
7	N	cub.	—	—	0.71	N^{5+}	0.1–0.2	—	—
8	O	orthorh.	—	—	0.60	O^{2-}	1.32	1.15	3.1
9	F	—	—	—	—	F^-	1.33	0.57	0.99
10	Ne	f.c.c.	12	3.20	1.60	—	—	—	—
11	Na	b.c.c.	8	3.71	1.92	Na^+	0.98	1.04	0.21
12	Mg	c.p.h.	6, 6	3.19; 3.20	1.60	Mg^{2+}	0.78	3.29	0.12
13	Al	f.c.c.	12	2.86	1.43	Al^{3+}	0.57	9.23	0.065
14	Si	d.	4	2.35	[1.17]	Si^{4-}	1.98	—	—
						Si^{4+}	0.39	26.30	0.043
15	P	orthorh.	3	2.18	[1.09]	P^{5+}	0.3–0.4	—	—
16	S	f.c. orthorh.	—	2.12	[1.04]	S^{2-}	1.74	0.66	7.25
						S^{6+}	0.34	51.90	—
17	Cl	orthorh.	1	2.14	[1.07]	Cl^-	1.81	0.30	3.05
18	A	f.c.c.	12	3.84	1.92	—	—	—	—
19	K	b.c.c.	8	4.62	2.38	K^+	1.33	0.57	0.85
20	Ca	f.c.c.	12	3.93	1.97	Ca^{2+}	1.06	1.78	0.57
		c.p.h.	6,6	3.98; 3.99	2.00				
21	Sc	f.c.c.	12	3.20	1.60	Sc^{3+}	0.83	4.35	0.38
		c.p.h.	6, 6	3.23; 3.30	1.64				
22	Ti	c.p.h.	6, 6	2.91; 2.95	1.47	Ti^{2+}	0.76	—	—
						Ti^{3+}	0.69	—	—
						Ti^{4+}	0.64	9.76	0.27
23	V	b.c.c.	8	2.63	1.36	V^{3+}	0.65	—	—
						V^{4+}	0.61	—	—
						V^{5+}	~0.4	—	—
24	Cr	b.c.c. (α)	8	2.49	1.28	Cr^{3+}	0.64	—	—
		c.p.h. (β)	6, 6	2.71; 2.72	1.36	Cr^{6+}	0.3 – 0.4	—	—
25	Mn	cub. (α)	—	2.24 – 2.96	[1.12]	Mn^{2+}	0.91	—	—
		cub. (β)	—	2.36 – 2.68	[1.18]	Mn^{3+}	0.70	—	—
		f.c.t. (γ)	8, 4	2.58; 2.67	~1.37	Mn^{4+}	0.52	—	—
26	Fe	b.c.c. (α)	8	2.48	1.28	Fe^{2+}	0.87	—	—
		f.c.c. (γ)	12	2.52	1.26	Fe^{3+}	0.67	—	—
27	Co	c.p.h. (α)	6, 6	2.49; 2.51	1.25	Co^{2+}	0.82	—	—
		f.c.c. (β)	12	2.51	1.26	Co^{3+}	0.65	—	—
28	Ni	c.p.h. (α)	6, 6	2.49; 2.49	1.25	Ni^{2+}	0.78	—	—
		f.c.c. (β)	12	2.49	1.25				
29	Cu	f.c.c.	12	2.55	1.28	Cu^+	0.96	—	—
30	Zn	c.p.h.	6, 6	2.66; 2.91	1.37	Zn^{2+}	0.83	2.90	—
31	Ga	orthorh.	—	2.43 – 2.79	1.35	Ga^{3+}	0.62	7.80	—
32	Ge	d.	4	2.44	1.39	Ge^{4+}	0.44	20.66	—
33	As	r.	3, 3	2.51; 3.15	[1.25]	As^{3+}	0.69	—	—
						As^{5+}	~0.4	—	—
34	Se	hex.	2, 4	2.32; 3.46	[1.16]	Se^{2-}	1.91	0.55	6.4
						Se^{6-}	0.3 – 0.4	—	—
35	Br	orthorh.	1	2.38	[1.19]	Br^-	1.96	0.26	4.17
36	Kr	f.c.c.	12	3.94	1.97	—	—	—	—

Table 4.25 ATOMIC AND IONIC RADII—*continued*

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
			As element				*In ionic crystals*		
Atomic number	*Symbol*	*Type of structure*	*Co-ordination No.*	*Inter-atomic distances*	*Goldschmidt at. radii*	*State of ionization*	*Goldschmidt ionic radii*	*polarizing power*	*polarizability*
37	Rb	b.c.c.	8	4.87	2.51	Rb^+	1.49	0.45	1.81
38	Sr	f.c.c.	12	4.30	2.15	Sr^{2+}	1.27	1.24	1.42
39	Y	c.p.h.	6, 6	3.59; 3.66	1.81	Y^{3+}	1.06	2.67	1.04
40	Zr	c.p.h. b.c.c.	6, 6 8	3.16; 3.22 3.12	1.60 1.61	Zr^{4+}	0.87	5.28	—
41	Nb	b.c.c.	8	2.85	1.47	Nb^{4+} Nb^{3+}	0.69 0.69	— 10.50	— —
42	Mo	b.c.c.	8	2.72	1.40	Mo^{4+} Mo^{6+}	0.68 0.65	— —	— —
43	Tc	—	—	—	—	—	—	—	—
44	Ru	c.p.h.	6, 6	2.64; 2.70	1.34	Ru^{4+}	0.65	—	—
45	Rh	f.c.c.	12	2.68	1.34	Rh^{3+} Rh^{4+}	0.68 0.65	— —	— —
46	Pd	f.c.c.	12	2.75	1.37	Pd^{2-}	0.50	—	—
47	Ag	f.c.c.	12	2.88	1.44	Ag^+	1.13	0.78	—
48	Cd	c.p.h.	6, 6	2.97; 3.29	1.52	Cd^{2+}	1.03	1.88	—
49	In	f.c.t.	4, 8	3.24; 3.37	1.57	In^{3+}	0.92	3.54	—
50	Sn	d. tetra.	4 4, 2	2.80 3.02; 3.18	1.58 —	Sn^{4-} Sn^{4+}	2.15 0.74	— 7.30	— —
51	Sb	r.	3, 3	2.90; 3.36	1.61	Sb^{3+}	0.90	—	—
52	Te	hex.	2, 4	2.86; 3.46	[1.43]	Te^{2-} Te^{4+}	2.11 0.89	0.45 —	9.6 —
53	I	orthorh	—	2.70	[1.36]	I^- I^{5+}	2.20 0.94	0.21 —	6.28 —
54	Xe	f.c.c.	12	4.36	2.18	—	—	—	—
55	Cs	b.c.c.	8	5.24	2.70	Cs^+	1.65	0.37	2.79

4.5 X-ray fluorescence

X-ray fluorescence occurs after an electron has been ejected from a shell surrounding the nucleus of an atom. The X-radiation is characteristic of the atom from which the electron has been ejected, and hence provides a means of identifying the atomic species. The ejection of an electron may be induced by irradiating the sample with photons (X or γ-rays) electrons, protons, charged particles or, indeed, any radiation capable of creating vacancies in the inner shells of the atoms of interest in the sample. The relative merits of each technique are given in Table 4.26. A further comparison of X-ray or radio-isotope sources for X-ray fluorescent spectroscopy is given in Table 4.27. Details of suitable available isotope sources are given in Table 4.28.

Analysis of fluorescent X-rays is achieved by wavelength dispersion using crystal analyser (or several in a multichannel instrument), or by energy dispersion with solid-state detectors. Wavelength dispersion offers more accurate quantitative analysis, especially for the detection of small concentrations of elements where X-ray spectra from several elements overlap. Energy dispersion is preferred when rapid or quantitative analysis is required of an unknown sample.

Examples of the detection limits for X-ray excited samples are given in Tables 4.29 and 4.30, and for ion excited samples in Table 4.31.

Accuracy levels for elemental analysis are typically:

for X-ray excitation	better than 1%.
for electron and ion excitation	1–2%.

These values can be improved with very carefully calibrated standards, but are frequently much worse, especially when the specimen surface is rough. Unlike X-ray diffraction, powdered samples are the most difficult sample form to analyse.

Table 4.25 ATOMIC AND IONIC RADII—*continued*

1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
				As element				*In ionic crystals*	
Atomic number	*Symbol*	*Type of structure*	*Co-ordination No.*	*Inter-atomic distances*	*Gold-schmidt at. radii*	*Stage of ionization*	*Gold-schmidt ionic radii*	*Polarizing power*	*polariza-bility*
56	Ba	b.c.c.	8	4.34	2.24	Ba^{2+}	1.43	0.98	2.08
57	La	c.p.h.	6, 6	3.72; 3.75	1.87	La^{3+}	1.22	2.01	1.56
		f.c.c.	12	3.75	1.87				
58	Ce	c.p.h.	6, 6	3.63; 3.65	1.82	Ce^{3+}	1.18	—	—
		f.c.c.	12	3.63	1.82	Ce^{4+}	1.02	3.84	1.20
59	Pr	hex.	6, 6	3.63; 3.66	1.83	Pr^{3+}	1.16	—	—
		f.c.c.	12	3.64	1.82	Pr^{4+}	1.00	—	—
60	Nd	hex.	6, 6	3.62; 3.65	1.82	Nd^{3+}	1.15	—	—
61	—	—	—	—	—	—	—	—	—
62	Sm	—	—	—	—	Sm^{3+}	1.13	—	—
63	Eu	b.c.c.	8	3.96	2.04	Eu^{3+}	1.13	—	—
64	Gd	c.p.h.	6, 6	3.55; 3.62	1.80	Gd^{3+}	1.11	—	—
65	Tb	c.p.h.	6, 6	3.51; 3.59	1.77	Tb^{3+}	1.09	—	—
						Tb^{4+}	0.89	—	—
66	Dy	c.p.h.	6, 6	3.50; 3.58	1.77	Dy^{3+}	1.07	—	—
67	Ho	c.p.h.	6, 6	3.48; 3.56	1.76	Ho^{3+}	1.05	—	—
68	Er	c.p.h.	6, 6	3.46; 3.53	1.75	Er^{3+}	1.04	—	—
69	Tm	c.p.h.	6, 6	3.45; 3.52	1.74	Tm^{3+}	1.04	—	—
70	Yb	f.c.c.	12	3.87	1.93	Yb^{3+}	1.00	—	—
71	Lu	c.p.h.	6, 6	3.44; 3.51	1.73	Lu^{3+}	0.99	—	—
72	Hf	c.p.h.	6, 6	3.13; 3.20	1.59	Hf^{4+}	0.84	—	—
73	Ta	b.c.c.	8	2.85	1.47	Ta^{5+}	0.68	—	—
74	W	b.c.c. (α)	8	2.74	1.41	W^{4+}	0.68	—	—
		cub. (β)	12; 2, 4	2.82; 2.52 2.82	1.41	W^{6+}	0.65	—	—
75	Re	c.p.h.	6, 6	2.73; 2.76	1.38	—	—	—	—
76	Os	c.p.h.	6, 6	2.67; 2.73	1.35	Os^{4+}	0.67	—	—
77	Ir	f.c.c.	12	2.71	1.35	Ir^{4+}	0.66	—	—
78	Pt	f.c.c.	12	2.77	1.38	Pt^{2+}	0.52	—	—
						Pt^{4+}	0.55	—	—
79	Au	f.c.c.	12	2.88	1.44	Au^{+}	1.37	—	—
80	Hg	r.	6	3.00	1.55	Hg^{2+}	1.12	1.59	—
81	Tl	c.p.h.	6, 6	3.40; 3.45	1.71	Tl^{+}	1.49	—	—
		b.c.c.	8	3.36	1.73	Tl^{3+}	1.06	2.72	—
82	Pb	f.c.c.	12	3.49	1.75	Pb^{4-}	2.15	—	—
						Pb^{2+}	1.32	—	—
						Pb^{4+}	0.84	5.67	—
83	Bi	r.	3, 3	3.11; 3.47	1.82	Bi^{3+}	1.20	—	—
84	Po	monocl.	—	2.81	[1.40]	—	—	—	—
85	At	—	—	—	—	—	—	—	—
86	Rn	—	—	—	—	—	—	—	—
87	Fr	—	—	—	—	—	—	—	—
88	Ra	—	—	—	—	Ra^{+}	1.52	—	—
89	Ac	—	—	—	—	—	—	—	—
90	Th	f.c.c.	12	3.60	1.80	Th^{4+}	1.10	3.31	—
91	Pa	—	—	—	—	—	—	—	—
92	U	orthorh.	—	2.76	[1.38]	U^{4+}	1.05	—	—
93	Np	—	—	—	—	—	—	—	—
94	Pu	—	—	—	—	—	—	—	—
95	Am	—	—	—	—	—	—	—	—
96	Cm	—	—	—	—	—	—	—	—

Table 4.26 COMPARISON OF X-RAY FLUORESCENCE TECHNIQUES

Exciting radiation	*Advantages*	*Limitations*
Electrons	High-intensity energy-regulated sources easily produced Can be focused into submicron spot size Low cost Good light element detection	Specimen must be in vacuum with source Signal-to-background ratio relatively poor
Positive ions	Better signal-to-background ratio than electrons Can be focused Very sensitive to low concentrations	Specimens must be in vacuum with source Expensive equipment
Photons X-rays or γ-rays	Convenient — specimen need not be in vacuum Widely used Wavelength can be chosen for maximum sensitivity for element of interest	Cannot be focused Not as sensitive to small samples as positive ion excited methods Light elements (< Mg difficult)

Table 4.27 COMPARISON OF X-RAY AND RADIOACTIVE SOURCES FOR X-RAY FLUORESCENT SPECTROSCOPY

Radiation source	*Advantages*	*Limitations*
X-rays	Controllable high-intensity source which can be switched off when not required Intensity can be 10^2–10^4 times that of radio-isotope source	Bulky, expensive equipment — requires high voltage generator
Radio isotopes	Cheaper, portable, and smaller than X-ray systems Can be built into process plant for local on-stream analysis	Permanent radioactive hazard Low intensity means long exposure times and/or larger samples Relatively small number of available isotopes (*see* Table 4.28)

Table 4.28 RADIO-ISOTOPE SOURCES FOR X-RAY FLUORESCENCE

Nuclide	*Half-life*	*Emission energies* keV
^{55}Fe	2.7 years	5.9
^{109}Cd	453 days	22.1, 87.7
^{125}I	60 days	27
^{241}Am	458 years	12.17, 60
^{57}Co	270 days	6.4, 1.22, 144
^{238}Pu	86.4 years	12–17

Source: Jaklevic and Goulding, in ref. 27, p. 33.

4.6 Radiation screening

In using X-rays, radioisotopes or accelerator-based sources of radiation, exposure to individuals must be controlled to be as low as is reasonably practicable but in any event to be less than the values indicated in Table 4.32. In most countries, persons processing, using, selling or transporting radioactive materials must be licensed by a national authority. In England the authority is the Department of the Environment, in Wales it is the Welsh Office, and in Scotland it is the Scottish Development Department.

Table 4.29 3σ DETECTION LIMITS FOR X-RAY EXCITED SAMPLES

	Experimental conditions			
	Wavelength dispersion Cr tube 2 500 W 100 s *analysis time*	*Energy dispersive Ag tube* 10 min *analysis time*		
		Ag *filter* 1.8 W	Ag + W *filter* 22 W	
Element	3σ *Detection limits in* 10^{-9} gcm^{-2}			
Mg	2	80		
Al	3	40		
Si	3	20		
S	9	12		
Cl	9	16		
Ca	2	28		
Fe	18		140	Fe impurity in Be window
Zn	7		30	
Br	28		20	
Pb	30		50	

Source: J. V. Gilfrich, in ref. 27, p. 405.

Table 4.30 3σ DETECTION LIMITS FOR BULK SAMPLES

	Experimental conditions: Wavelength dispersion; All measurements in p.p.m.	
Element	*Iron and steel sample W target,* 2 240 W 10 min *analysis time*	Fe *and* Ni *base alloys W target* 2025 W 100 s
Si	170	4
P		35
S		8
Ti	1.0	
V	1.9	
Cr	4.0	1
Mn	1.4	5
Ni	5.4	
Ca	8.5	12
As	6.8	
Zr	4.6	
Mo	4.5	22
Sn	3.9	

Source: J. V. Gilfrich, in ref. 27, p. 408.

Table 4.31 EXAMPLES OF DETECTION LIMITS FOR ION EXCITATION

Sample mount	*Ions*	*Energy* MeV	*Current or charge*	*Time*	*Detection limit*	*Detection limit criterion*
1 mg cm^{-2} VYNS	α	50	1 nA	400 s	Cu 1.9×10^{-12} g Sn 3.2×10^{-12} g Pb 5.5×10^{-12} g	P/B = 0.1
10–20 μg cm^{-2} carbon or nitrocellulose	p^+	5	5 μC	100–200 s	K 1×10^{-9} g cm^{-2} Cu 2×10^{-9} g cm^{-2} Br 1×10^{-9} g cm^{-2} Au 5×10^{-9} g cm^{-2}	3σ Bgd
	α	5	5 μC	100–200 s	K 1×10^{-9} g cm^{-2} Br 10×10^{-9} g cm^{-2} Au 20×10^{-9} g cm^{-2}	3σ Bgd
40 μg cm^{-2} carbon	p^+	1.5	5 μA	30 min	Ca 0.3×10^{-12} g Cu 1×10^{-12} g Ba 20×10^{-12} g Pb 10×10^{-12} g	100 counts above Bgd

Table 4.31 EXAMPLES OF DETECTION LIMITS FOR ION EXCITATION— *continued*

Sample mount	*Ions*	*Energy* MeV	*Current or charge*	*Time*	*Detection limit*	*Detection limit criterion*
4 μm Mylar	p^+	1	10 μC	500 s	Ca 7×10^{-9} g cm^{-2} Zn 18×10^{-9} g cm^{-2} Zr 300×10^{-9} g cm^{-2} Pb 90×10^{-9} g cm^{-2}	3σ Bgd
		0.3	10 μC	500 s	Ca 3×10^{-9} g cm^{-2} Zn 5×10^{-9} g cm^{-2} Zr 30×10^{-9} g cm^{-2} Pb 23×10^{-9} g cm^{-2}	3σ Bgd

Source: J. V. Gilfrich, in ref. 27, p. 406.

4.6.1 Definitions

Exposure

Exposure is a measure of the intensity of ionizing radiation multiplied by time. It is measured in coulombs per kilogram (C kg^{-1}) in SI units. An exposure of 1 C kg^{-1} implies the production of a stated number of ion pairs per unit mass of air.

Absorbed dose

Absorbed dose is a measure of the energy absorbed per unit mass in a stated material when exposed to ionizing radiation under stated conditions. It is measured in grays (Gy) in SI units. 1 Gy = 1 J kg^{-1}.

Dose equivalent

An absorbed dose has a biological effect which depends upon the type of ionizing radiation and on the end-effect under consideration. The relationship between the absorbed dose (A) and dose equivalent (D) is determined by the quality factor (Q) (originally described as relative biological effectiveness) in the equation

$$D = Q \times A$$

Dose equivalent is measured in sieverts (Sv) in SI units. 1 Sv = 1 J kg^{-1}. Q is approximately 1 for X-rays, γ-rays and electrons; it is in the range of approximately 1–11 for neutrons, and can be as high as 20 for α particles.

Dose may be received from external radiation or, following an intake of radioactive material, from internal radiation. Dose received from internal radiation is called committed dose. The terms dose equivalent and committed dose equivalent refer to dose received by individual organs or tissues, etc, from external and internal radiation respectively. The corresponding terms for dose received by the whole body are effective dose equivalent and committed effective dose equivalent respectively. The dose limits given in Table 4.32 refer to the sum of external and internal dose for the part of the body concerned (unless stated otherwise).

External dose to the whole body is normally taken in practice to be the penetrating component of the dose measured by a film badge or thermoluminescent dosemeter worn on or near the chest or trunk of the body, plus any neutron dose measured by a neutron badge.

Table 4.32 CURRENT STATUTORY DOSE LIMITS (Ionizing Radiations Regulations 1985)

Organ, tissue, or part of body	Annual limit for occupationally exposed employees aged 18 or over (10 mSv = 1 rem)
Whole body	50 mSv
Individual organ or tissue (other than the lens of the eye), body extremity or skin	500 mSv
Lens of the eye	150 mSv

Activity

The SI unit of activity is the becquerel (Bq), equal to one nuclear transformation per second.

In the UK, in addition to the annual dose limits, the Health and Safety Executive requires that an investigation be carried out forthwith when any adult employee receives a whole body dose greater than three-tenths of the dose limit, i.e. 15 mSv, in a calendar year. Notification to the Executive is required if an adult employee receives a whole body dose greater than three-fifths of the dose limit, i.e. 30 mSv, in any calendar quarter.

Adult female occupationally exposed persons

As in Table 4.32 and above, but abdomen dose, from external radiation, in any three consecutive months not to exceed 13 mSv; after declaration of pregnancy, abdomen dose, from external radiation, for remainder of pregnancy not to exceed 10 mSv.

Young persons

No person under 16 years of age should be employed in work which may involve exposure to ionizing radiation. Persons who are over 16 but under 18 years of age are limited to 0.3 times the maximum doses set out in Table 4.32.

Other persons

All other persons are limited to one tenth of the annual maximum permissible doses set out in Table 4.32.

Table 4.33 THICKNESS OF CONCRETE REQUIRED TO REDUCE BROAD BEAM PULSATING OR CONSTANT POTENTIAL X-RAYS BY THE TRANSMISSION FACTOR GIVEN

Transmission factor		1/10	1/100	1/1000	1/10000	1/100000	1/1000000
Tube potential kV	*Total filtration* mm Al	*Concrete thickness* cm					
50	1.0	1	2	3	4.5	6	7
70	1.5	2	4.5	8	12	15.5	19.5
100	2.0	3.5	8.5	14	19.5	25	30.5
125	3.0	4.0	10.5	17	23.5	30	36.5
150	3.0	5.5	12.5	19.5	26.5	33.5	41
200	3.0	6.5	15	23.5	32	40.5	49
250	3.0	7.5	17	26	35	44.5	54
300	3.0	8.0	18	28	38	48	58
300	3.0Cu	13	22	31.5	41	50.5	60
400	3.0Cu	14	24	34	44	54	64

Table 4.34 THICKNESS OF LEAD REQUIRED TO REDUCE BROAD BEAM PULSATING POTENTIAL X-RAYS BY THE TRANSMISSION FACTOR GIVEN

Transmission factor		1/10	1/100	1/1000	1/10000	1/100000	1/1000000
Tube potential kV	*Total filtration* mm Al	*Lead thickness* cm					
50	1.8	0.01	0.02	0.04	0.065	0.085	0.11
75	3.8	0.015	0.05	0.10	0.155	0.215	0.27
100	4.0	0.023	0.075	0.15	0.24	0.330	0.417
125	3.2	0.03	0.085	0.165	0.26	0.36	0.46
150	3.2	0.035	010	0.185	0.28	0.38	0.48
200	3.3	0.055	0.13	0.25	0.39	0.53	0.68
250	3.0Cu	0.08	0.24	0.46	0.72	1.02	1.32
300	4.0Cu	0.17	0.46	0.88	1.32	1.80	2.30

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5 Crystallography

5.1 The structure of crystals

5.1.1 Translation groups

Metals and alloys, like most solid matter, are aggregates of crystals; they are built up of units, consisting of small groups of atoms regularly and indefinitely repeated throughout the body by parallel translations. If the co-ordinates of the atoms within such a group are given, then three independent translations represented by vectors $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$, which are not all parallel to the same plane, suffice to specify the position of any other atom in the crystal. Let the vector from an arbitrary origin to an atom be

$$r = xa + yb + zc$$

then atoms of the same kind will be found at all points

$$r_n = (n_1 + x)a + (n_2 + y)b + (n_3 + z)c$$

where n_1, n_2, n_3 may be any positive or negative integers. Such a succession of regularly arranged points in space constitutes a space lattice.

The lattice may be regarded either as a system of translations relating identical points in a structure, or as a system of points arranged in parallel and equidistant nets, each net consisting of series of parallel and equidistant rows in which the points are spaced at equal distances. The points of such an array can be arbitrarily arranged in an infinite number of ways in parallel equidistant linear rows or planar nets; they can, in other words, be referred to an infinite number of systems of three primitive vectors, but investigation has shown that any structure possessing the symmetry observed in crystals can be referred to one of 14 lattices, defined by its primitive vectors and by the character of its unit cell, the latter being the parallelepiped formed by the three translations selected as units. In general, unit translations are selected so as to give the simplest cell having edges as short as possible, but there are several cases in which a more complex cell is chosen so as to display the symmetry of the lattice, or its relation to other lattices, to greater advantage.

The system of three vectors $\boldsymbol{a}, \boldsymbol{b}, \boldsymbol{c}$, is described by their lengths a, b, c and by the angles between them: $(bc) = \alpha$, $(ca) = \beta$, $(ab) = \gamma$. The face of the unit cell which is parallel to the plane of the (a) and (b) axes, and which therefore intersects the (c) axis at distance c from the origin is termed the c face. Similarly, the face parallel to the b–c axial plane is the a face, and that parallel to the a–c axial plane the b face.

The simplest cell, having points only at its corners, is termed 'primitive' and is given the symbol Γ (Schoenflies) or P (Hermann). Other cells, termed 'face centred', have points at the corners and at the centres of two or more of their faces, and are given symbols indicating the faces carrying these additional points. Thus A, B, C, F represent centring on the a, b, c and all faces respectively. Finally there is the 'body centred' cell, having points at its corners and one additional point at the intersection of the body diagonals. This is given the symbol I (Hermann). Centred cells are indicated by Schoenflies by dashes. The 14 lattices are listed in Table 5.1.

5.1.2 Symmetry elements

Symmetry elements may be classified as axes, planes, and centres. A body has an axis of symmetry when rotation through a definite angle about some line through it (the axis of rotation) causes it to

Table 5.1 THE FOURTEEN LATTICES

System	*Axes*	*Angles*	*Unit cells*	*Symbols*	
				Schoenflies	*Hermann*
Triclinic	$a \neq b \neq c$	$\alpha \neq \beta \neq \gamma$	Primitive	Γtr	P
Monoclinic	$a \neq b \neq c$	$\alpha = \gamma = 90°$ β obtuse	*1* Primitive *2* c face centred	Γm $\Gamma m'$	P C*
Orthorhombic	$a \neq b \neq c$	$\alpha = \beta = \gamma = 90°$	*1* Primitive *2* Face centred *3* All face centred *4* Body centred	Γo $\Gamma o'(c)$ $\Gamma o''$ Γ'''	P C† F† I
Tetragonal	$a = b \neq c$	$\alpha = \beta = \gamma = 90°$	*1* Primitive *2* Body centred	Γt $\Gamma t'$	P I
Cubic	$a = b = c$	$\alpha = \beta = \gamma = 90°$	*1* Primitive *2* All face centred *3* Body centred	Γc $\Gamma c'$ $\Gamma c''$	P F I
Rhombohedral	$a = b = c$	$\alpha = \beta = \gamma \neq 90°$	Primitive	Γrh	R
Hexagonal	$a = b \neq c$	$\alpha = \beta = 90°$ $\gamma = 120°$	Primitive	Γh	C‡

* By choosing different a and b axes the c-centred monoclinic cell will be seen to be equivalent to a primitive cell in which $a = b \neq c$, $\alpha = \beta = 90°$, $\gamma \neq \alpha$. Even if these axes are selected, the symbol C is retained for this cell.

† By suitable change of axes it is possible to convert the orthorhombic C and F cells into primitive and body centred cells respectively having $a = b \neq c$, $\alpha = \beta = 90°$, γ obtuse. The symbols for these alternative settings remain C and F.

‡ This is a special form of the alternative setting described in the preceding note for the orthorhombic C cell. It is therefore given the symbol C.

assume its original aspect. Crystals have been observed to have axes of 2-, 3-, 4- and 6-fold reflection, involving coincidence after rotation through 180°, 120°, 90° and 60° respectively. If a plane can be passed through a body such that every point on one side of the plane stands in mirror-image relationship to a corresponding point on the other side, the plane is said to be a reflecting plane or plane of symmetry. A point within a body is a centre of symmetry or centre of inversion if a line drawn from any point of the body to the centre and extended to an equal distance beyond it encounters a corresponding point. Other symmetry operations are:

Rotary reflection, involving rotation through a definite angle, combined with reflection in a plane normal to the axis.
Screw axes of rotation, combining rotation about an n-fold axis with a translation of a specified length in the direction of the axis.
Glide planes, combining reflection with a translation parallel to the plane of the mirror.

In the case of screw axes, the amount of the shift must be a rational fraction of the translation along the same axis, the denominator of the fraction being the multiplicity of the rotation. Thus for a 6-fold axis, the shift may be 1/6, 2/6, 3/6 ... of the translation. In the case of the glide plane, the shift must be one half of some translation in that plane. Thus it may be $a/2$ or $b/2$ parallel to the a and b axes, or of half the face diagonal in the direction parallel to that diagonal. If the cell is centred on that particular face, the shift may be one half of the distance to the centre, i.e. of the face diagonal.

5.1.3 The point group

The point group may be defined as a group of symmetry elements distributed about a point in space, and may be conveniently visualized as an assembly of points generated by the operation of the symmetry elements in question upon a single point having co-ordinates xyz referred to specified axes, the symmetry elements passing through the origin. Thus a symmetry plane, passing through the origin and containing the x and y axes, will generate, from the point xyz, an equivalent point of which the co-ordinates are $xy\bar{z}$. These two points serve to characterize the point group.

The 32-point groups define all the ways in which axes, planes and centres of symmetry can be distributed so as to intersect in a point in space, and correspond to the 32 classes of morphological crystallography.

5.1.4 The space group

The space group may be defined as an extended network of symmetry elements distributed about the points of a space lattice, and may be visualized as an assembly of points generated by the operation of symmetry elements on a series of points situated identically in each cell of the lattice. Whereas in the point group the repeated operation of any symmetry element must ultimately bring each point back to its original position, in the space group an operation need only bring the point to an analogous position in the same or in another cell of the lattice. Thus in the space group the more complex symmetry operation of screw axes and glide planes are possible, combining translation with reflection and rotation.

Point groups, placed at the points of space lattices belonging to the same system of symmetry, give rise to the simplest of the 230 space groups. The remainder are generated by replacing the simple planes and axes of the point group by glide planes and screw axes.

5.2 The Schoenflies system of point- and space-group notation

The symmetry elements chosen by Schoenflies are axes of n-fold rotation, reflection planes and centres of inversion. The symbols assigned to the various point groups are as follows:

C_n = groups having a single n-fold axis.
C_n^h = groups having a single vertical n-fold axis, together with a horizontal reflection plane
C_n^v = groups having a single vertical n-fold axis, together with n vertical reflection planes
D_n = groups having an n-fold axis and n two-fold axes at right angles to it
V = a symbol frequently used as an alternative to D_2
O = the two cubic groups which possess the maximum possible number of rotation axes, namely four 4-fold axes parallel to the cube edges, four 3-fold axes parallel to the cube diagonals and six 2-fold axes parallel to the face diagonals
T = the three remaining groups of the cubic system
S_n = groups having an n-fold axis of rotary reflection

The suffix i signifies a centre of inversion.
The suffix s signifies a single plane of symmetry.
The suffix d signifies a diagonal reflection plane, bisecting the angle between two horizontal axes.

The symbols for the space groups are simple modifications of those for the point groups: the index and subscript of the point group are combined to give the subscript of the space group symbol, and an index is added representing the order in which Schoenflies deduced the symmetry of the group. Thus C_{nh}^m represents the mth group derived from the point group C_n^h.

Table 5.2 gives the point groups, their symbols and elements of symmetry, the crystal classes with which they correspond, and the co-ordinates of equivalent points.

5.3 The Hermann–Mauguin system of point- and space-group notation

The symbols used by Hermann and Mauguin to indicate the various symmetry operations are as follows:

Rotation axes: the number 2, 3, 4 or 6 denoting the multiplicity.
Screw axes: the symbol denoting the multiplicity of rotation, with a subscript indicating the magnitude of the shift. The complete set of screw axes is 2_1; 3_1; 3_2; 4_1, 4_2, 4_3; 6_1, 6_2, 6_3, 6_4, 6_5.
Axes of rotary reflection: $\bar{2}$, $\bar{3}$, $\bar{4}$, $\bar{6}$, the numeral indicating the multiplicity.
Centre of inversion: $\bar{1}$.
Reflection plane: m.
Glide plane: with shift in the a direction: a
with shift in the b direction: b
with shift of $\frac{1}{2}$ the face diagonal: n
with shift of $\frac{1}{2}$ the centring translation: d.

The full space group symbol consists of the translation (or lattice) symbol followed by symbols of the symmetry elements associated with specified crystallographic directions in a specified order. The direction associated with a reflection or glide plane is that of its normal: no direction can be specified for a centre of inversion.

Table 5.2 POINT-GROUP

System	*Class no.*	*Schoenflies symbol*	*Crystal class*		
			Schoenflies	*Dana*	*Miers*
Triclinic	1	C_1	Hemihedry	Asymmetric	Asymmetric
	2	C_i	Holohedry	Normal	Central
Monoclinic	3	$C_s = C_1^h$	Hemihedry	Clinohedral	Planar
	4	C_2	Hemimorphic hemihedry	Hemimorphic	Digonal polar
	5	C_2^h	Holohedry	Normal	Digonal equatorial
Orthorhombic	6	C_2^v	Hemimorphic hemihedry	Hemimorphic	Didigonal polar
	7	$V = D_2$	Enantiomorphic hemihedry	Sphenoidal	Digonal holoaxial
	8	$V^h = D_2^h$	Holohedry	Normal	Didigonal equatorial
Tetragonal	9	S_4	Tetartohedry of 2nd sort	Tetartohedral	Tetragonal alternating
	10	$V^4 = D_2^d$	Hemihedry of 2nd sort	Sphenoidal	Ditetragonal alternating
	11	C_4	Tetartohedry	Pyramidal hemimorphic	Tetragonal polar
	12	C_4^h	Paramorphic hemihedry	Pyramidal	Tetragonal equatorial
	13	C_4^v	Hemimorphic hemihedry	Hemimorphic	Ditetragonal polar
	14	D_4	Enantiomorphic hemihedry	Trapezohedral	Tetragonal holoaxial
	15	D_4^h	Holohedry	Normal	Ditetragonal equatorial
Cubic	16	T	Tetartohedry	Tetartohedral	Tesseral polar
	17	T^h	Paramorphic hemihedry	Pyritohedral	Tesseral central
	18	T^d	Hemimorphic hemihedry	Tetrahedral	Ditesseral polar
	19	O	Enantiomorphic hemihedry	Plagihedral	Tesseral holoaxial
	20	O^h	Holohedry	Normal	Ditesseral central
Rhombohedral	21	C_3	Tetartohedry	Not named	Trigonal polar
	22	$C_3^i = S_5$	Hexagonal tetartohedry of 2nd sort	Trirhombohedral	Hexagonal alternating
	23	C_3^v	Hemimorphic hemihedry	Ditrigonal pyramidal	Ditrigonal polar
	24	D_3	Enantiomorphic hemihedry	Trapezohedral	Trigonal holoaxial
	25	D_3^d	Holohedry	Rhombohedral	Dihexagonal alternating
Hexagonal	26	C_3^h	Trigonal paramorphic hemihedry	Not named	Trigonal equatorial
	27	D_3^h	Trigonal holohedry	Trigonotype	Ditrigonal equatorial
	28	C_6	Tetartohedry	Pyramidal hemimorphic	Hexagonal polar
	29	C_6^h	Paramorphic hemihedry	Pyramidal	Hexagonal equatorial
	30	C_6^v	Hemimorphic hemihedry	Hemimorphic	Dihexagonal polar
	31	D_6	Enantiomorphic hemihedry	Trapezohedral	Hexagonal holoaxial
	32	D_6^h	Holohedry	Normal	Dihexagonal equatorial

NOTATION (SCHOENFLIES)

Typical example	*Symmetry elements*	*Co-ordinates of equivalent points*
	None	xyz
Copper sulphate	Centre of inversion	xyz, $\bar{x}\bar{y}\bar{z}$
—	Horizontal reflecting plane	xyz, $xy\bar{z}$
Tartaric acid	2-fold axis	xyz, $\bar{x}\bar{y}z$
Gypsum	2-fold axis and horizontal plane	xyz, $\bar{x}\bar{y}z$, $xy\bar{z}$, $\bar{x}\bar{y}\bar{z}$
Topaz	2-fold axis and vertical plane	xyz, $\bar{x}\bar{y}z$, $\bar{x}yz$, $x\bar{y}z$
Sulphur	Three 2-fold axes	xyz, $x\bar{y}\bar{z}$, $\bar{x}y\bar{z}$, $\bar{x}\bar{y}z$
Barytes	Three 2-fold axes and horizontal plane	xyz, $x\bar{y}\bar{z}$, $\bar{x}y\bar{z}$, $\bar{x}\bar{y}z$, $xy\bar{z}$, $x\bar{y}z$, $\bar{x}yz$, $\bar{x}\bar{y}\bar{z}$
—	4-fold rotary reflection	xyz, $\bar{y}x\bar{z}$, $\bar{x}\bar{y}z$, $y\bar{x}\bar{z}$
Chalcopyrite	4-fold axis, two 2-fold axes and diagonal vertical plane	xyz, $x\bar{y}\bar{z}$, $\bar{x}y\bar{z}$, $\bar{x}\bar{y}z$, yxz, $\bar{y}x\bar{z}$, $y\bar{x}\bar{z}$, $\bar{y}\bar{x}z$
Wulfenite	4-fold axis	xyz, $\bar{y}xz$, $\bar{x}\bar{y}z$, $y\bar{x}z$
Scheelite	4-fold axis, horizontal plane	xyz, $\bar{y}xz$, $\bar{x}\bar{y}z$, $y\bar{x}z$, $xy\bar{z}$, $\bar{y}x\bar{z}$, $\bar{x}\bar{y}\bar{z}$, $y\bar{x}\bar{z}$
—	4-fold axis, vertical plane	xyz, $\bar{y}xz$, $\bar{x}\bar{y}z$, $y\bar{x}z$, $\bar{x}yz$, yxz, $x\bar{y}z$, $\bar{y}\bar{x}z$
—	4-fold axis and four 2-fold axes	xyz, $\bar{y}xz$, $\bar{x}\bar{y}z$, $y\bar{x}z$, $x\bar{y}\bar{z}$, $\bar{y}\bar{x}\bar{z}$, $\bar{x}y\bar{z}$, yxz
Zircon	4-fold axis, four 2-fold axes, horizontal plane	xyz, $\bar{y}xz$, $\bar{x}\bar{y}z$, $y\bar{x}z$, $x\bar{y}\bar{z}$, $\bar{y}\bar{x}\bar{z}$, $\bar{x}y\bar{z}$, $\bar{y}x\bar{z}$ $xy\bar{z}$, $\bar{y}x\bar{z}$, $\bar{x}\bar{y}\bar{z}$, $y\bar{x}\bar{z}$, $x\bar{y}z$, $\bar{y}\bar{x}z$, $\bar{x}yz$, yxz
Ullmanite	Three 2-fold axes coincident with cube axes, *and* Four 3-fold axes coincident with cube diagonals	xyz, $x\bar{y}\bar{z}$, $\bar{x}y\bar{z}$, $\bar{x}\bar{y}z$ zxy, $\bar{z}x\bar{y}$, $\bar{z}\bar{x}y$, $zx\bar{y}$ yzx, $\bar{y}\bar{z}x$, $y\bar{z}\bar{x}$, $\bar{y}zx$
Pyrites	As for T plus a horizontal plane	Those of T plus xyz, $x\bar{y}\bar{z}$, $\bar{x}yz$, $\bar{x}\bar{y}z$; $zx\bar{y}$, zxy, $\bar{z}\bar{x}\bar{y}$, $z\bar{x}y$; yzx, $\bar{y}\bar{z}\bar{x}$, $y\bar{z}x$, $\bar{y}zx$
Blende	As for T plus a diagonal vertical plane	Those of T plus yxz, $\bar{y}x\bar{z}$, $y\bar{x}\bar{z}$, $\bar{y}\bar{x}z$; xzy, $x\bar{z}\bar{y}$, $\bar{x}\bar{z}y$, $\bar{x}z\bar{y}$; zyx, $\bar{z}\bar{y}x$, $\bar{z}y\bar{x}$, $z\bar{y}\bar{x}$
Cuprite	As for T plus six 2-fold axes coincident with face diagonals thereby converting the three original 2-fold axes into 4-folds	Those of T plus $\bar{y}\bar{x}\bar{z}$, $y\bar{x}z$, $\bar{y}xz$, yxz; $\bar{x}\bar{z}\bar{y}$, $\bar{x}zy$, $xz\bar{y}$, $x\bar{z}y$; $\bar{z}\bar{y}\bar{x}$, $zy\bar{x}$, $z\bar{y}x$, $\bar{z}yx$
Galena	As for O plus a horizontal plane	Those of all the four preceding classes
—	3-fold axis	xyz, zxy, yzx referred to rhombohedral axes
Dioptase	3-fold axis and centre of inversion	xyz, zxy, yzx, $\bar{x}\bar{y}\bar{z}$, $\bar{z}\bar{x}\bar{y}$, $\bar{y}\bar{z}\bar{x}$ (rhombohedral axes)
Tourmaline	3-fold axis and vertical plane	xyz, zxy, yzx, yxz, xzy, zyx (rhombohedral axes)
Quartz	3-fold axis and three 2-fold axes	xyz, zxy, yzx, $\bar{y}x\bar{z}$, $\bar{x}z\bar{y}$, $\bar{z}\bar{y}\bar{x}$ (rhombohedral axes)
Calcite	3-fold axis, three 2-fold axes and diagonal vertical planes	xyz, zxy, yzx, $\bar{y}\bar{x}\bar{z}$, $\bar{x}\bar{z}\bar{y}$, $\bar{z}\bar{y}\bar{x}$ $\bar{x}\bar{y}\bar{z}$, $\bar{z}\bar{x}y$, $\bar{y}\bar{z}x$, yxz, xzy, zyx (rhombohedral axes)
—	3-fold axis and horizontal plane	xyz, $(y-x)\bar{x}z$, $\bar{y}(x-y)z$, $xy\bar{z}$, $(y-x)\bar{x}\bar{z}$, $\bar{y}(x-y)\bar{z}$ (hexagonal axes)
—	3-fold axis, three 2-fold axes and horizontal plane	xyz, $(y-x)\bar{x}z$, $\bar{y}(x-y)z$, $(x-y)\bar{y}\bar{z}$, $yx\bar{z}$, $\bar{x}(y-x)z$ $xy\bar{z}$, $(y-x)x\bar{z}$, $\bar{y}(x-y)\bar{z}$, $(x-y)\bar{y}z$, yxz, $\bar{x}(y-x)z$ (hexagonal axes)
Nepheline	6-fold axes	xyz, $y(y-x)z$, $(y-x)\bar{x}z$, $\bar{x}\bar{y}z$, $\bar{y}(x-y)z$, $(x-y)xz$ (hexagonal axes)
Apatite	6-fold axis and horizontal plane	Those of C_6 plus xyz, $y(y-x)\bar{z}$, $(y-x)\bar{x}\bar{z}$, $\bar{x}\bar{y}\bar{z}$, $\bar{y}(x-y)\bar{z}$, $(x-y)x\bar{z}$ (hexagonal axes)
Greenockite	6-fold axis and vertical plane	Those of C_6 plus $\bar{x}(y-x)z$, $(y-x)yz$, yxz, $x(x-y)z$, $(x-y)\bar{y}z$, $\bar{y}\bar{x}z$ (hexagonal axes)
—	6-fold axis and six 2-fold axes	Those of C_6 plus $\bar{x}(y-x)\bar{z}$, $(y-x)y\bar{z}$, $xy\bar{z}$, $x(x-y)\bar{z}$ $(x-y)\bar{y}\bar{z}$, $\bar{y}\bar{x}\bar{z}$ (hexagonal axes)
Beryl	6-fold axis, six 2-fold axes and horizontal plane	Those of all the four preceding classes

The specified directions are:

Triclinic system: none
Monoclinic system: the **b** direction, i.e. the *b* axis.
Orthorhombic system: the **a**, **b**, **c** directions, in that order.
Tetragonal, *Hexagonal*, *Rhombohedral* systems: the **a**, **b**, and (**a**–**b**) directions, in that order. The direction represented by the vector difference is one of the diagonals of the *c*-face.
Cubic system: the directions **c**, (**a** + **b** + **c**) and (**a** − **b**), in that order, i.e. the *c*-axis the cube diagonal and a diagonal of the *c*-face.

If a symmetry axis has a symmetry plane normal to it, the two symbols are combined in the form of a fraction, thus $\frac{2}{m}$, $\frac{4_1}{d}$, alternatively written $2/m$, $4_1/d$.

If one of the specified crystallographic directions has no symmetry element associated with it, this is indicated by inserting the symbol 1 in the appropriate position in the space group symbol. The 1 may be omitted without risk of misunderstanding if it occurs at the end of the space group symbol. Symmetry symbols may also be omitted if they can be derived from those already indicated. These abbreviated symbols are termed 'short'.

As already explained, the symmetry of a space group can be derived from that of a point group by placing the latter at the points of the various lattices appropriate to the crystal system, and by using glide planes and screw axes as well as reflection planes and rotation axes. Thus the point group symbol will contain no symbol for the lattice; its symmetry planes will be indicated by *m* and its axes by numbers specifying the multiplicity and without subscripts. Thus the point group $2/m$ will be associated with the space groups $P(2/m)$; $P(2_1/m)$; $P(2/c)$; $P(2_1/c)$; $C(2/m)$; and $C(2/c)$.

5.3.1 Notes on the space-group tables

For a full description of the space groups, reference should be made to the *Internationale Tabellen zur Bestimmung von Kristallstrukturen.*

If there are *n* symmetry elements associated with any space group, their operation upon any single point having co-ordinates *xyz* will give rise to a total of *n* points which may be termed geometrically equivalent. If, however, the co-ordinates *xyz* are such that the point lies, say, on an axis or plane of symmetry, then the number of equivalent positions will be reduced, while if it lies at the intersection of two elements the number will be reduced still further. A knowledge of these so-called special positions is of importance, because experience has shown that they are the positions which are frequently occupied by the atoms or ions in an actual crystal. In sodium chloride, for example, the four sodium ions are situated in one set of four equivalent positions, those having co-ordinates 000, $\frac{1}{2}\frac{1}{2}0$, $\frac{1}{2}0\frac{1}{2}$, $0\frac{1}{2}\frac{1}{2}$, whilst the four chlorine ions are situated in another set of four points, having co-ordinates $\frac{1}{2}\frac{1}{2}\frac{1}{2}$, $00\frac{1}{2}$, $0\frac{1}{2}0$, $\frac{1}{2}00$. The co-ordinates of all the special positions for each space group were given by R. W. G. Wyckoff in *The Analytical Expression of the Results of the Theory of Space Groups* (Washington Carnegie Institution, 1930) and are also listed in the *Internationale Tabellen.*

The last column of Table 5.3 gives the missing x-ray reflections characteristic of each space group. If the unit cell is centred on one or more faces, or is body centred, certain reflections will be absent, because in directions corresponding to the missing reflections the waves scattered by the atoms at the face or body centres will be exactly out of phase with those scattered by the atoms at the cell corners. In other words, the spacings of certain planes are halved, and odd-order reflections from these planes are destroyed. Thus with the body-centred lattice all reflections are absent for which $(h + k + l)$ is odd. Again, a glide plane halves the spacings in the direction of glide, and a 2-fold screw axis halves those along the axis. Consequently, odd order reflections are missing in these directions. Similarly with a 3-fold axis; the only reflections occurring in the direction of the axis are those for which (l) is a multiple of three.

In Table 5.3, x-ray reflections of the type indicated do not occur unless indices which are underlined are even, or unless the sum of indices joined together by brackets is even. Thus:

$00\underline{l}$ means that reflections will not occur unless l is even.

$0\underline{k}\underline{l}$ means that reflections will not occur unless $(k + l)$ is even.

$\underline{h}\underline{k}0$ means that reflections will not occur unless both h and k are even.

$\underline{h}\underline{k}\underline{l}$ means that reflections will not occur unless $(h + k + l)$ is even.

$\underline{hkl}$ means that reflections will not occur unless the sums of any two indices are even.

$\underline{hhl}$ means that reflections will not occur if the first two indices are equal, unless the third index, l, is even.

A subscript 3, 4 or 6 means that the marked index, or the sum of the marked indices, must be a multiple of that number for reflections to occur. Thus

$0\underline{kl}_4$ means that reflections will not occur unless $(k + l)$ is a multiple of 4.

$\underline{hkl}_3$ means that reflections will not occur unless $h + 2k + l$ is a multiple of 3.

Table 5.3 THE HERMANN-MAUGUIN SYSTEM OF POINT- AND SPACE-GROUP NOTATION

Space group Hermann–Mauguin *Full*	*Short*	*Schoenflies*	*Missing spectra*
Triclinic system			
Class 1—C_1			
$P1$		C_1^1	—
Class 1—C_i			
$P\bar{1}$		C_i^1	—
Monoclinic system			
Class m—C_s			
Pm		C_s^1	—
Pc		C_s^2	$h0\underline{l}$
Cm		C_s^3	$\underline{hkl}$
Cc		C_s^4	$\underline{hkl}$, $h0\underline{l}$
Class 2—C_2			
$P2$		C_2^1	—
$P2_1$		C_2^2	$0\underline{k}0$
$C2$		C_2^3	$\underline{hkl}$
Class $\frac{2}{m}$—C_{2h}			
$P\frac{2}{m}$		C_{2h}^1	—
$P\frac{2_1}{m}$		C_{2h}^2	$0\underline{k}0$
$P\frac{2}{c}$		C_{2h}^4	$h0\underline{l}$
$P\frac{2_1}{c}$		C_{2h}^5	$h0\underline{l}$, $0\underline{k}0$
$C\frac{2}{m}$		C_{2h}^3	$\underline{hkl}$
$C\frac{2}{c}$		C_{2h}^6	$\underline{hkl}$, $h0\underline{l}$
Orthorhombic system			
Class $mm2$ (short mm)—C_{2v}			
$Pmm2$	Pmm	C_{2v}^1	—
$Pmc2_1$	Pmc	C_{2v}^2	$h0\underline{l}$
$Pma2$	Pma	C_{2v}^4	$\underline{h}0\underline{l}$
$Pmn2_1$	Pmn	C_{2v}^7	$\underline{hol}$
$Pcc2$	Pcc	C_{2v}^3	$0\underline{kl}$, $h0\underline{l}$
$Pca2_1$	Pca	C_{2v}^5	$0\underline{kl}$, $\underline{h}0\underline{l}$
$Pcn2$	Pcn	C_{2v}^6	$0\underline{kl}$, $\underline{hol}$
$Pba2$	Pba	C_{2v}^8	$0\underline{kl}$, $\underline{h}0\underline{l}$
$Pbn2_1$	Pbn	C_{2v}^9	$0\underline{kl}$, $\underline{hol}$
$Pnn2$	Pnn	C_{2v}^{10}	$0\underline{kl}$, $\underline{hol}$
$Cmm2$	Cmm	C_{2v}^{11}	$\underline{hkl}$
$Cmc2_1$	Cmc	C_{2v}^{12}	$\underline{hkl}$, $h0\underline{l}$
$Ccc2$	Ccc	C_{2v}^{13}	$\underline{hkl}$, $0\underline{kl}$, $h0\underline{l}$
$Amm2$	Amm	C_{2v}^{14}	$\underline{hkl}$
$Ama2$	Ama	C_{2v}^{16}	$\underline{hkl}$, $\underline{h}0\underline{l}$
$Abm2$	Abm	C_{2v}^{15}	$\underline{hkl}$, $0\underline{kl}$
$Aba2$	Aba	C_{2v}^{17}	$\underline{hkl}$, $0\underline{kl}$, $h0\underline{l}$
$Fmm2$	Fmm	C_{2v}^{18}	$\underline{hkl}$
$Fdd2$	Fdd	C_{2v}^{19}	$\underline{hkl}$, $0\underline{kl}_4$, $h0\underline{l}_4$
$Imm2$	Imm	C_{2v}^{20}	$\underline{hkl}$
$Ima2$	Ima	C_{2v}^{22}	$\underline{hkl}$, $\underline{h}0\underline{l}$
$Iba2$	Iba	C_{2v}^{21}	$\underline{hkl}$, $0\underline{kl}$, $h0\underline{l}$
Class 222 (short 22)—$D_2(V)$			
$P222$		$D_2^1(V^1)$	—
$P222_1$		$D_2^2(V^2)$	$00\underline{l}$
$P2_12_12$		$D_2^3(V^3)$	$\underline{h}00$, $0\underline{k}0$
$P2_12_12_1$		$D_2^4(V^4)$	$\underline{h}00$, $0\underline{k}0$, $00\underline{l}$
$C222$		$D_2^5(V^5)$	$\underline{hkl}$
$C222_1$		$D_2^6(V^6)$	$\underline{hkl}$, $00\underline{l}$
$F222$		$D_2^7(V^7)$	$\underline{hkl}$
$I222$		$D_2^8(V^8)$	$\underline{hkl}$
$I2_12_12_1$		$D_2^9(V^9)$	$\underline{hkl}$

Table 5.3 THE HERMANN-MAUGUIN SYSTEM OF POINT- AND SPACE-GROUP NOTATION—*continued*

Space group Hermann–Mauguin *Full*	*Short*	*Schoenflies*	*Missing spectra*
Class $\frac{2\,2\,2}{m\,m\,m}$ (short *mmm*)—$D_{2h}(V_h)$			
$P\frac{2\,2\,2}{m\,m\,m}$	*Pmmm*	$D^1_{2h}(V_h^1)$	—
$P\frac{2_1\,2_1\,2}{m\,m\,n}$	*Pmmn*	$D^{13}_{2h}(V_h^{13})$	$hk0$
$P\frac{2_1\,2_1\,2}{n\,n\,m}$	*Pnnm*	$D^{12}_{2h}(V_h^{12})$	$0kl$, $h0l$
$P\frac{2\,2\,2}{n\,n\,n}$	*Pnnn*	$D^2_{2h}(V_h^2)$	$0kl$, $h0l$, $hk0$
$P\frac{2_1\,2\,2}{m\,m\,a}$	*Pmma*	$D^5_{2h}(V_h^5)$	$hk0$
$P\frac{2\,2_1\,2}{n\,n\,a}$	*Pnna*	$D^6_{2h}(V_h^6)$	$0kl$, $h0l$, $hk0$
$P\frac{2\,2\,2_1}{m\,n\,a}$	*Pmna*	$D^7_{2h}(V_h^7)$	$h0l$, $hk0$
$P\frac{2_1\,2_1\,2_1}{n\,m\,a}$	*Pnma*	$D^{16}_{2h}(V_h^{16})$	$0kl$, $hk0$
$P\frac{2_1\,2_1\,2}{b\,a\,m}$	*Pbam*	$D^9_{2h}(V_h^9)$	$0kl$, $h0l$
$P\frac{2\,2\,2}{b\,a\,n}$	*Pban*	$D^4_{2h}(V_h^4)$	$0kl$, $h0l$, $hk0$
$P\frac{2\,2\,2}{c\,c\,m}$	*Pccm*	$D^3_{2h}(V_h^3)$	$0kl$, $h0l$
$P\frac{2_1\,2_1\,2}{c\,c\,n}$	*Pccn*	$D^{10}_{2h}(V_h^{10})$	$0kl$, $h0l$, $hk0$
$P\frac{2\,2_1\,2_1}{b\,c\,m}$	*Pbcm*	$D^{11}_{2h}(V_h^{11})$	$0kl$, $h0l$
$P\frac{2_1\,2\,2_1}{b\,c\,n}$	*Pbcn*	$D^{14}_{2h}(V_h^{14})$	$0kl$, $h0l$, $hk0$
$P\frac{2_1\,2_1\,2_1}{b\,c\,a}$	*Pbca*	$D^{15}_{2h}(V_h^{15})$	$0kl$, $h0l$, $hk0$
$P\frac{2_1\,2\,2}{c\,c\,a}$	*Pcca*	$D^8_{2h}(V_h^8)$	$0kl$, $h0l$, $hk0$
$C\frac{2\,2\,2}{m\,m\,m}$	*Cmmm*	$D^{19}_{2h}(V_h^{19})$	hkl
$C\frac{2\,2\,2}{m\,m\,a}$	*Cmma*	$D^{21}_{2h}(V_h^{21})$	hkl, $hk0$
$C\frac{2\,2\,2}{c\,c\,m}$	*Cccm*	$D^{20}_{2h}(V_h^{20})$	hkl, $0kl$, $h0l$
$C\frac{2\,2\,2}{c\,c\,a}$	*Ccca*	$D^{22}_{2h}(V_h^{22})$	hkl, $0kl$, $h0l$, $hk0$
$C\frac{2\,2\,2_1}{m\,c\,m}$	*Cmcm*	$D^{17}_{2h}(V_h^{17})$	hkl, $h0l$
$C\frac{2\,2\,2_1}{m\,c\,a}$	*Cmca*	$D^{18}_{2h}(V_h^{18})$	hkl, $h0l$, $hk0$
$F\frac{2\,2\,2}{m\,m\,m}$	*Fmmm*	$D^{23}_{2h}(V_h^{23})$	hkl
$F\frac{2\,2\,2}{d\,d\,d}$	*Fddd*	$D^{24}_{2h}(V_h^{24})$	hkl, $0kl_4$, $h0l_4$, $hk0_4$
$I\frac{2\,2\,2}{m\,m\,m}$	*Immm*	$D^{25}_{2h}(V_h^{25})$	hkl
$I\frac{2\,2\,2}{b\,a\,m}$	*Ibam*	$D^{26}_{2h}(V_h^{26})$	hkl, $0kl$, $h0l$
$I\frac{2_1\,2_1\,2_1}{m\,m\,a}$	*Imma*	$D^{28}_{2h}(V_h^{28})$	hkl, $hk0$
$I\frac{2_1\,2_1\,2_1}{b\,c\,a}$	*Ibca*	$D^{27}_{2h}(V_h^{27})$	hkl, $0kl$, $h0l$, $hk0$
Tetragonal system			
Class $\bar{4}$—S_4			
$P\bar{4}$		S_4^1	—
$I\bar{4}$		S_4^2	hkl
Class 4—C_4			
$P4$		C_4^1	—
$P4_2$		C_4^3	$00l$
$P4_1$, $P4_3$		C_4^2, C_4^4	$00l_4$
$I4$		C_4^5	hkl
$I4_1$		C_4^6	hkl, $00l_4$
Class $\frac{4}{m}$—C_{4h}			
$P\frac{4}{m}$		C_{4h}^1	—
$P\frac{4}{n}$		C_{4h}^3	$hk0$
$P\frac{4_2}{m}$		C_{4h}^2	$00l$
$P\frac{4_2}{n}$		C_{4h}^4	$hk0$, $00l$
$I\frac{4}{m}$		C_{4h}^5	hkl
$I\frac{4_1}{a}$		C_{4h}^6	hkl, $hk0$ $00l_4$
Class $\bar{4}2m$ (or, in other orientation, $\bar{4}m2$)—$D_{2d}(V_d)$			
$P\bar{4}2m$		$D_{2d}^1(V_d^1)$	—

Table 5.3 THE HERMANN–MAUGUIN SYSTEM OF POINT- AND SPACE-GROUP NOTATION—*continued*

Space group Hermann–Mauguin *Full*	*Short*	*Schoenflies*	*Missing spectra*
Class $\bar{4}2m$ (or, in other orientation, 4m2)—$D_{2d}(V_d)$—*continued*:			
	$P\bar{4}2c$	$D_{2d}^{2}(V_d^{2})$	hhl
	$P\bar{4}2_1m$	$D_{2d}^{3}(V_d^{3})$	$h00$
	$P\bar{4}2_1c$	$D_{2d}^{4}(V_d^{4})$	hhl, $h00$
	$P\bar{4}m2$	$D_{2d}^{5}(V_d^{5})$	—
	$P\bar{4}c2$	$D_{2d}^{6}(V_d^{6})$	$0kl$
	$P\bar{4}b2$	$D_{2d}^{7}(V_d^{7})$	$0kl$
	$P\bar{4}n2$	$D_{2d}^{8}(V_d^{8})$	$0kl$
	$I\bar{4}2m$	$D_{2d}^{11}(V_d^{11})$	hkl
	$I\bar{4}2d$	$D_{2d}^{12}(V_d^{12})$	hkl, hhl_4
	$I\bar{4}m2$	$D_{2d}^{9}(V_d^{9})$	hkl
	$I\bar{4}c2$	$D_{2d}^{10}(V_d^{10})$	hkl, $0kl$
Class $4mm$—C_{4v}			
$P4mm$	$P4mm$	C_{4v}^{1}	—
$P4_2mc$	$P4mc$	C_{4v}^{7}	hhl
$P4_2cm$	$P4cm$	C_{4v}^{3}	$0kl$
$P4cc$	$P4cc$	C_{4v}^{5}	$0kl$, hhl
$P4bm$	$P4bm$	C_{4v}^{2}	$0kl$
$P4_2bc$	$P4bc$	C_{4v}^{8}	$0kl$, hhl
$P4_2nm$	$P4nm$	C_{4v}^{4}	$0kl$
$P4nc$	$P4nc$	C_{4v}^{6}	$0kl$, hhl
$I4mm$	$I4mm$	C_{4v}^{9}	hkl
$I4cm$	$I4cm$	C_{4v}^{10}	hkl, $0kl$
$I4_1md$	$I4md$	C_{4v}^{11}	hkl, hhl_4
$I4_1cd$	$I4cd$	C_{4v}^{12}	hkl, $0kl$ hhl_4
Class 422 (short 42)—D_4			
$P422$	$P42$	D_4^{1}	—
$P4_422$	$P4_22$	D_4^{5}	$00l$
$P4_122$	$P4_12$	D_4^{3}	$00l_4$
$P4_322$	$P4_32$	D_4^{7}	
$P42_12$	$P42_1$	D_4^{2}	$h00$
$P4_22_12$	$P4_22_1$	D_4^{6}	$00l$, $h00$
$P4_12_12$	$P4_12_1$	D_4^{4}	$00l_4$, $h00$
$P4_32_12$	$P4_32_1$	D_4^{8}	
$I422$	$I422$	D_4^{9}	hkl
$I4_122$	$I4_12$	D_4^{10}	hkl, $00l_4$
Class $\frac{4}{m}\frac{2}{m}\frac{2}{m}$ (short $4/mmm$)—D_{4h}			
$P\frac{4}{m}\frac{2}{m}\frac{2}{m}$	$P4/mmm$	D_{4h}^{1}	—

Space group Hermann–Mauguin *Full*	*Short*	*Schoenflies*	*Missing spectra*
Class $\frac{4}{m}\frac{2}{m}\frac{2}{m}$ (short $4/mmm$)—D_{4h}—*continued*			
$P\frac{4_2}{m}\frac{2}{m}\frac{2}{c}$	$P4_2/mmc$	D_{4h}^{9}	hhl
$P\frac{4_2}{m}\frac{2}{c}\frac{2}{m}$	$P4_2/mcm$	D_{4h}^{10}	$0kl$
$P\frac{4}{m}\frac{2}{c}\frac{2}{c}$	$P4/mcc$	D_{4h}^{2}	$0kl$, hhl
$P\frac{4}{m}\frac{2_1}{b}\frac{2}{m}$	$P4/mbm$	D_{4h}^{5}	$0kl$
$P\frac{4_2}{m}\frac{2_1}{b}\frac{2}{c}$	$P4_2/mbc$	D_{4h}^{13}	$0kl$, hhl
$P\frac{4_2}{m}\frac{2_1}{n}\frac{2}{m}$	$P4_2/mnm$	D_{4h}^{14}	$0kl$
$P\frac{4}{m}\frac{2_1}{n}\frac{2}{c}$	$P4/mnc$	D_{4h}^{6}	$0kl$, hhl
$P\frac{4}{n}\frac{2_1}{m}\frac{2}{m}$	$P4/nmm$	D_{4h}^{7}	$hk0$
$P\frac{4_2}{n}\frac{2_1}{m}\frac{2}{c}$	$P4_2/nmc$	D_{4h}^{15}	$hk0$, hhl
$P\frac{4_2}{n}\frac{2_1}{c}\frac{2}{m}$	$P4_2/ncm$	D_{4h}^{16}	$hk0$, $0kl$
$P\frac{4}{n}\frac{2_1}{c}\frac{2}{c}$	$P4/ncc$	D_{4h}^{8}	$hk0$, $0kl$, hhl
$P\frac{4}{n}\frac{2}{b}\frac{2}{m}$	$P4/nbm$	D_{4h}^{3}	$hk0$, $0kl$
$P\frac{4_2}{n}\frac{2}{b}\frac{2}{c}$	$P4_2/nbc$	D_{4h}^{11}	$hk0$, $0kl$, hhl
$P\frac{4_2}{n}\frac{2}{n}\frac{2}{m}$	$P4_2/nnm$	D_{4h}^{12}	$hk0$, $0kl$
$P\frac{4}{n}\frac{2}{n}\frac{2}{c}$	$P4/nnc$	D_{4h}^{4}	$hk0$, $0kl$, hhl
$I\frac{4}{m}\frac{2}{m}\frac{2}{m}$	$I4/mmm$	D_{4h}^{17}	hkl
$I\frac{4}{m}\frac{2}{c}\frac{2}{m}$	$I4/mcm$	D_{4h}^{18}	hkl, $0kl$
$I\frac{4_1}{a}\frac{2}{m}\frac{2}{d}$	$I4_1/amd$	D_{4h}^{19}	hkl, $hk0$, hhl_4
$I\frac{4_1}{a}\frac{2}{c}\frac{2}{d}$	$I4_1/acd$	D_{4h}^{20}	hkl, $hk0$, $0kl$, hhl_4
Cubic system			
Class 23—T			
	$P23$	T^{1}	—
	$P2_13$	T^{4}	$h00$

Table 5.3 THE HERMANN–MAUGUIN SYSTEM OF POINT- AND SPACE-GROUP NOTATION—*continued*

Space group Hermann–Mauguin Full	Short	*Schoen-flies*	*Missing spectra*
Class 23—*T*—*continued*			
	$F23$	T^2	$\underline{hkl}$
	$I23$	T^3	$\underline{hkl}$
	$I2_13$	T^5	$\underline{hkl}$
Class $\frac{2}{m}\bar{3}$ (short $m3$)—T_h			
$P\frac{2}{m}\bar{3}$	$Pm3$	T_h^1	—
$P\frac{2}{n}\bar{3}$	$Pn3$	T_h^2	$hk0$
$P\frac{2_1}{a}\bar{3}$	$Pa3$	T_h^6	$\underline{h}k0$
$F\frac{2}{m}\bar{3}$	$Fm3$	T_h^3	$\underline{hkl}$
$F\frac{2}{d}\bar{3}$	$Fd3$	T_h^4	$\underline{hkl}$, $hk0$
$I\frac{2}{m}\bar{3}$	$Im3$	T_h^5	$\underline{hkl}$
$I\frac{2_1}{a}\bar{3}$	$Ia3$	T_h^7	$\underline{hkl}$, $\underline{h}k0$
Class $\bar{4}3m$—T_d			
	$P\bar{4}3m$	T_d^1	—
	$P\bar{4}3n$	T_d^4	hh
	$F\bar{4}3m$	T_d^2	$\underline{hkl}$
	$F\bar{4}3c$	T_d^5	$\underline{hkl}$, $\underline{k}hl$
	$I\bar{4}3m$	T_d^3	$\underline{hkl}$
	$I\bar{4}3d$	T_d^6	$\underline{hkl}$, $\underline{hhl}_4$
Class 432—*O*			
$P432$	$P43$	O^1	—
$P4_232$	$P4_23$	O^2	$h00$
$P4_132$	$P4_13$	O^7	$\underline{h}_4 00$
$P4_332$	$P4_33$	O^6	
$F432$	$F43$	O^3	$\underline{hkl}$
$F4_132$	$F4_13$	O^4	$\underline{hkl}$, $\underline{h}_4 00$
$I432$	$I43$	O^5	$\underline{hkl}$
$I4_132$	$I4_13$	O^8	$\underline{hkl}$, $\underline{h}_4 00$
Class $\frac{4}{m}\bar{3}\frac{2}{m}$ short $m3m$)—O_h			
$P\frac{4}{m}\bar{3}\frac{2}{m}$	$Pm3m$	O_h^1	--
Class $\frac{4}{m}\bar{3}\frac{2}{m}$ (short $m3m$)—O_h—*continued*			
$P\frac{4_2}{m}\bar{3}\frac{2}{n}$	$Pm3n$	O_h^3	$\underline{hhl}$
$P\frac{4_2}{n}\bar{3}\frac{2}{m}$	$Pn3m$	O_h^4	$\underline{hk}0$
$P\frac{4}{n}\bar{3}\frac{2}{n}$	$Pn3n$	O_h^2	$\underline{hk}0$, $\underline{hhl}$
$F\frac{4}{m}\bar{3}\frac{2}{m}$	$Fm3m$	O_h^5	$\underline{hkl}$
$F\frac{4}{m}\bar{3}\frac{2}{c}$	$Fm3c$	O_h^6	$\underline{hkl}$, $\underline{hhl}$
$F\frac{4_1}{d}\bar{3}\frac{2}{m}$	$Fd3m$	O_h^7	$\underline{hkl}$, $\underline{hk}0_4$
$F\frac{4_1}{d}\bar{3}\frac{2}{c}$	$Fd3c$	O_h^8	$\underline{hkl}$, $\underline{hk}0_4$, $\underline{hhl}$
$I\frac{4}{m}\bar{3}\frac{2}{m}$	$Im3m$	O_h^9	$\underline{hkl}$
$I\frac{4_1}{a}\bar{3}\frac{2}{d}$	$Ia3d$	O_h^{10}	$\underline{hkl}$, $\underline{hk}0$, $\underline{hhl}_4$
Rhombohedral system (all indices and multiplicities referred to hexagonal axes)			
Class 3—C_3			
	$C3$	C_3^1	—
	$C3_1, C3_2$	C_3^2, C_3^3	$00\underline{l}$
	$R3$	C_3^4	$\underline{hkl}_3$
Class $\bar{3}$—C_{3i}			
	$C\bar{3}$	C_{3i}^1	—
	$R\bar{3}$	C_{3i}^2	$\underline{hkl}_3$
Class $3m$ (to indicate orientation distinguish $3m1$ and $31m$)—C_{3v}			
	$C3m1$	C_{3v}^1	—
	$C3c1$	C_{3v}^3	$h0\underline{l}$
	$C31m$	C_{3v}^2	—
	$C31c$	C_{3v}^4	$\underline{hhl}$
	$R3m$	C_{3v}^5	$\underline{hkl}_3$
	$R3c$	C_{3v}^6	$\underline{hkl}_3$, $h0\underline{l}$

Table 5.3 THE HERMANN–MAUGUIN SYSTEM OF POINT- AND SPACE-GROUP NOTATION—*continued*

Space group Hermann–Mauguin *Full*	*Short*	*Schoenflies*	*Missing spectra*
Class 32 (to indicate orientation distinguish 321 and 312)—$D3$			
$C321$		D_3^2	—
$C3_121$		D_3^4	$00l$
$C3_221$		D_3^6	
$C312$		D_3^1	—
$C3_112$		D_3^3	$00l$
$C3_212$		D_3^5	
$R32$		D_3^7	$\underline{hkl}_{-h+k+l=3n}$
Class $\bar{3}\frac{2}{m}$ (short $\bar{3}m$) (to indicate orientation distinguish $\bar{3}ml$ and $\bar{3}lm$)—D_{3d}			
$C\bar{3}\frac{2}{m}1$	$C\bar{3}m1$	D_{3d}^3	—
$C\bar{3}\frac{2}{c}1$	$C\bar{3}c1$	D_{3d}^4	$h0\underline{l}$
$C\bar{3}1\frac{2}{m}$	$C\bar{3}1m$	D_{3d}^1	—
$C\bar{3}1\frac{2}{c}$	$C\bar{3}1c$	D_{3d}^2	$hh\underline{l}$
$R\bar{3}\frac{2}{m}$	$R\bar{3}m$	D_{3d}^5	$\underline{hkl}_{-h+k+l=3n}$
$R\bar{3}\frac{2}{c}$	$R\bar{3}c$	D_{3d}^6	$\underline{hkl}_{-h+k+l=3n}$, $h0\underline{l}$
Hexagonal system			
Class $\bar{6}$—C_{3h}			
$C\bar{6}$		C_{3h}^1	—
Class $\bar{6}$—C_6			
$C6$		C_6^1	—
$C6_3$		C_6^6	$00\underline{l}$
$C6_2$, $C6_4$		C_6^4, C_6^5	$00\underline{l}$
$C6_1$, $C6_5$		C_6^2, C_6^3	$00\underline{l}$
Class $\frac{6}{m}$—C_{6h}			
$C\frac{6}{m}$		C_{6h}^1	—
$C\frac{6_3}{m}$		C_{6h}^2	$00\underline{l}$
Class $\bar{6}2m$ (in other orientation $\bar{6}m2$)—D_{3h}			
$C\bar{6}2m$		D_{3h}^3	—
$C\bar{6}2c$		D_{3h}^4	$hh\underline{l}$
$C\bar{6}m2$		D_{3h}^1	—
$C\bar{6}c2$		D_{3h}^2	$h0\underline{l}$
Class $6mm$—C_{6v}			
$C6mm$	$C6mm$	C_{6v}^1	—
$C6_3mc$	$C6mc$	C_{6v}^4	$hh\underline{l}$
$C6_3cm$	$C6cm$	C_{6v}^3	$h0\underline{l}$
$C6cc$	$C6cc$	C_{6v}^2	$h0\underline{l}$, $hh\underline{l}$
Class 622—D_6			
$C622$	$C62$	D_6^1	—
$C6_322$	$C6_32$	D_6^6	$00\underline{l}$
$C6_222$	$C6_22$	D_6^4	$00\underline{l}$
$C6_422$	$C6_42$	D_6^5	
$C6_122$	$C6_12$	D_6^2	$00\underline{l}$
$C6_522$	$C6_52$	D_6^3	
Class $\frac{6}{m}\frac{2}{m}\frac{2}{m}$ (short $6/mmm$)—D_{6h}			
$C\frac{6}{m}\frac{2}{m}\frac{2}{m}$	$C6/mmm$	D_{6h}^1	
$C\frac{6_3}{m}\frac{2}{m}\frac{2}{c}$	$C6/mmc$	D_{6h}^4	$hh\underline{l}$
$C\frac{6_3}{m}\frac{2}{c}\frac{2}{m}$	$C6/mcm$	D_{6h}^3	$h0\underline{l}$
$C\frac{6}{m}\frac{2}{c}\frac{2}{c}$	$C6/mcc$	D_{6h}^2	$h0\underline{l}$, $hh\underline{l}$

6 Crystal chemistry

6.1 Structures of metals, metalloids and their compounds

The elements have been arranged in the following order:

1. Group Ia—Li, Na, K, Rb, Cs
2. Group IIa—Be, Mg, Ca, Sr, Ba
3. Group IIIa—Sc, Y, La, Ce, Pr, Nd, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Ac
4. Group IVa—Ti, Zr, Hf, Th, Pa, U, Np, Pu, Am, Cm
5. Group Va—V, Nb, Ta
6. Group VIa—Cr, Mo, W
7. Group VIIa—Mn, Tc, Re
8. Group VIII—Fe, Co, Ni; Ru, Rh, Pd, Os, Ir, Pt
9. Group Ib—Cu, Ag, Au
10. Group IIb—Zn, Cd, Hg
11. Group IIIb—Al, Ga, In, Tl
12. Group IVb—Si, Ge, Sn, Pb
13. Group Vb—As, Sb, Bi
14. Metalloids etc.—B, C, P, N, Te, Se, S

A compound or solid solution composed of the elements ABCD... is placed under that element, A, B, C, D,... which occurs *last* in the above list. If there are several compounds containing this particular element, they are arranged in the following order:

(a) Compounds containing the same elements—in the order of increasing content of the second element.
(b) Compounds of different elements—in the order in which the other elements occur in the above list.

For example, Na_2K is described under K, because K comes after Na in the list; MgSr and Mg_2Sr are both entered under Sr, and are described in that order, in accordance with (a); Li_2Ca and Mg_2Ca are entered under Ca, and described in that order, in accordance with (b).

The second column of Table 6.1 gives the symbol for the structural type to which the element or compound is assigned, the notation used being that of *Strukturbericht*.* Detailed descriptions of the structural types are given in Table 6.2.

The third column of Table 6.1 gives the lattice constants of the various elements and compounds. For cubic crystals the single parameter a is given, in Å units; for tetragonal and hexagonal crystals a and c, in that order; for orthorhombic, a, b and c; for rhombohedral a, α; for monoclinic a, b, c, β.

Temperatures given in parentheses are those at which allotropic or polymorphic modifications are stable; figures such as $A = 28$, $M = 4$, also given in parentheses, refer to the number of atoms (A) or molecules (M) included in the unit cell; alternative structures are given where the available evidence is insufficient to permit of a decision being reached between them, and in such cases the authorities are quoted. Finally, it should be noted that in the case of the sulphides, only those having relatively simple structures have been included.

* Strukturbericht of *Z. Krystallographie*, Leipzig.

Although this system of classification is not used in any other compilation of intermetallic compounds, it has been retained as it has its own logic in keeping together compounds of similar systems in a Group; this would be lacking in a strictly alphabetical classification.

Since this compilation was first made, data on a very large number of intermetallic compounds have been published, far more than can be included in this list without extending it to over 1000 pages. Table 6.1 refers to the more frequently encountered compounds. Other compilations should be consulted for compounds not found in Table 6.1.

The most comprehensive database is: 'Pearson's Handbook of Crystallographic Data for Intermetallic Phases' (3 volumes) by P. Villars and L. D. Calvert, published by A.S.M., 1985 (new edition pending).

Pearson has introduced a new system of symbols based on the crystallography of the classes of isostructural compounds. This cannot be deduced readily from the Structurbericht Classification used in Table 6.1 and described in Table 6.2. Hence a comparison of the two nomenclatures is provided in Table 6.3.

The Pearson symbols take the form aBn, where:

a denotes the crystal system, i.e. cubic, hexagonal, etc.
B denotes the space lattice of the unit cells using the Hermann–Mauguin symbols, i.e. P, C, F, I, etc.
n denotes the number of atoms per unit cell.

The crystal systems are:

c = Cubic
h = Hexagonal
m = Monoclinic
o = Orthorhombic
t = Tetragonal

The space lattices of the unit cells are:

P = Simple
F = All Face-centred^{+}
I = Body-centred
C = One face-centred*
R = Simple (rhombohedral)

* Monoclinic and Orthorhombic
$^{+}$ Cubic and Orthorhombic
e.g. A1(Cu) is cF4 and C14($MgZn_2$) is hP12.

As will be evident from Table 6.3, a Pearson symbol can be the same for several different structural types or prototypes.

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group Ia: Li, Na, K, Rb, Cs			
Li	*A2*	3.5093	1
	A3	3.111; 5.093 (spontaneous transformation at −195°C)	
	A1	4.388 (produced by deformation at low temp.)	
Na	*A2*	4.2906	
	A1	5.34 (incomplete transformation by working at −253°C)	
K	*A2*	5.321	
Na_2K	*C14*	7.48; 12.27	
Rb	*A1*	5.705	
Cs	*A1*	6.141	
Group IIa: Be, Mg, Ca, Sr, Ba			
Be	*A3*	2.2859; 3.5845	
Be	*A3*	3.2094; 5.2107	
$Be_{13}Mg$	$D2_3$	10.166	2
Ca (α)	*A1*	5.5884 (< ~300°C)	
(γ)	*A3*	3.94; 6.46 (> ~450°C; a third modification of unknown structure exists in the range 300–450°C)	
Li_2Ca	*C14*	6.25; 10.23	
$Be_{13}Ca$	$D2_3$	10.312	2
Mg_2Ca	*C14*	6.22; 10.10	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIa: Be, Mg, Ca, Sr, Ba—*continued*			
Sr	*A1*	6.084	
MgSr	*B2*	3.90	
Mg_2Sr	*C14*	6.43; 10.47	
Ba	*A2*	5.0227	3
Mg_2Ba	*C14*	6.64; 10.66	
Group IIIa: Sc, Y and Rare Earths			
Sc (α)	*A1*	4.541	
(β)	*A3*	3.308; 5.267	207
Y	*A3*	3.6482; 5.7318	
$Be_{13}Y$	$D2_3$	10.24	
La (α)	*A3*	3.774; 12.171 (room temp.)	4
(β)	*A1*	5.31 (above 340°C)	4
MgLa	*B2*	3.97	
Mg_2La	*C15*	8.71	
Mg_3La	$D0_3$	7.47	
Ce (α)	*A3*	3.6810; 11.857	
(β)	*A1*	5.1612	4
(β')	*A1*	4.84 (under 15 000 atm. pressure; also formed at 90 K under atm. pressure	
$Be_{13}Ce$	$D2_3$	10.376	
MgCe	*B2*	3.90	
Mg_2Ce	*C15*	8.70 (range 615–750°C)	
Mg_3Ce	$D0_3$	7.42	
Pr	*A1*	5.15	
	A3	3.672; 11.835	4
MgPr	*B2*	3.88	
Mg_3Pr	$D0_2$	7.37	
Nd	*A3*	3.6582; 11.7966	207
Eu	*A2*	4.5827	208
Gd	*A3*	3.6336; 5.781	209
Tb		3.6055; 5.6966	
Dy		3.5915; 5.6501	
Ho		3.5778; 5.6178	
Er		3.5592; 5.585	210
Tm		3.5375; 5.554	
Yb	*A1*	5.4848	
Lu	*A3*	3.5052; 5.5494	
Ac	cubic f.c.	5.311	6
Group IVa: Ti, Zr, Hf, Th and Pa, U, Np, Pu, Am, Cm			
Ti (α)	*A3*	2.9506; 4.6835 ($< \sim 900$°C)	
(β)	*A2*	3.3065 ($> \sim 900$°C)	
$BeLi_4$	hex.	10.92; 8.94 ($M = 6$)	211
Be_2Ti	*C15*	6.44	
$Be_{12}Ti$	*D2a*	29.44; 7.33 (may be considered as *D2b* 7.35; 4.19)	
Ti_2Be_{17}	Th_2Ni_{17}	7.36; 7.30	
Ti_2Be_{17}	Nb_2Be_{17}	7.39; 10.79	
Zr (α)	*A3*	3.2316; 5.1475 ($< \sim 840$°C)	7
(β)	*A2*	3.6090 ($> \sim 840$°C)	7
Be_5Zr	*D2d*	4.56; 3.49	
$Be_{17}Zr_2$	$Be_{17}Nb_2$	7.55; 11.00	
Be_2Zr	*C32*	3.82; 3.24	8
$Be_{13}Zr$	$D2_3$	10.05	
Hf (α)	*A3*	3.1946, < 1310°C	9, 10
(β)	*A2*	3.61	
Hf_2Be_{17}	Nb_2Be_{17}	7.50; 10.94	213
$HfBe_{13}$	*D2b*	10.01	
$HfBe_5$	*D2d*	4.53; 3.47	
Th	*A1*	5.0842	
Th (ζ)	orthorh.	9.820; 8.164; 6.681	11

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IVa: Ti, Zr, Hf, Th and Pa, U, Np, Pu, Am, Cm—*continued*			
$B_{13}Th$	$D2_3$	10.40	
Mg_2Th	$C36$	6.086; 19.64 (at and below 700°C)	12
	$C15$	8.570 (at and above 800°C)	12
Pa	Aa	3.921; 3.235	13
U (α)	$A20$	2.854; 5.869; 4.955	214
(β)	tetr.	10.759; 5.656 (range 650–760°C)	14
("β")	Ab	10.763; 5.652 at 720°C	14
		10.590; 5.634 at room temp.	15
(γ)	$A2$	3.524 (>760°C)	
UH_3	$A15$	6.644 } the $A15$ type holds only for the U positions	
UD_3	$A15$	6.633 }	
$Be_{13}U$	$D2_3$	10.26	
TiU_2	$C32$	4.828; 2.847	16
Zr–U	cubic f.c.	10.68	17
Np (α)	Ac	(<278°C) 6.663; 4.723; 4.887	
(β)	Ad	4.883; 3.389 (range 278–540°C)	
(γ)	$A2$ (?)	3.52	18
$B_{13}Np$	$D2_3$	10.266 to 10.256	19
Pu (α)	monocl.	6.183 5; 4.824 4; 10.973; $\beta = 101.80$	20
(β)	monocl.	9.284; 10.463; 7.859 $B = 92.13°$ $A = 34$	215
(δ)	cubic f.c.	4.637	21
(δ')	tetr.	3.3261; 4.4630	21
(ε)	cubic b.c.	3.634 8	21
Am	$P6_3/mma$	3.468 1; 11.240	216
Group Va: V, Nb, Ta			
V	$A2$	3.024	22
Be_2V	$C14$	4.39; 7.14	
$Be_{12}V$	$D2b$	7.28; 4.21	
Be_2Nb_3	$D5a$	6.49; 3.35 ($M = 2$)	217
$Be_{17}Nb_2$	$R\bar{3}m$	5.599; 82.84° ($M = 1$)	218
$Be_{17}Nb_2$	$Be_{17}Nb_2$	7.41; 10.84	
$Be_{12}Nb$	$D2b$	7.34; 4.26	
Nb	$A2$	3.3004	
Ta	$A2$	3.3030	
$BeTa_2$	$C16$	6.01; 4.89	
$Be_{17}Ta_2$	$Be_{17}Nb_2$	7.39; 10.74	
Be_2Ta	$C15$	6.51	
ZrV_3	$C14$	5.28; 8.65	
TiV (ω)	orthorh.	6.205; 6.597; 13.63	219
Group VIa: Cr, Mo, W			
Cr (α)	$A2$	2.882 (<1840°C)	
(β)	$A1$	3.8848 (>1840°C)	
(γ)	$A12$	8.72 (electrolytic)	
~CrH	$B4$	2.72; 4.43	
$\sim CrH_2$	$C1$	3.86	
Be_2Cr	$C14$	4.26; 6.99	
$Be_{12}Cr$	$D2b$	7.23; 4.17	
TiCr (ω)	orthorh.	6.203; 6.498; 13.63	219
$TiCr_2$	$C15$	6.93 (Ti positions partly replaced by Cr)	
$ZrCr_2$ (1)	$C14$	5.079; 8.262	24
(2)	$C15$	7.195	24
$NbCr_2$	$C15$	6.98	
$TaCr_2$ (1)	$C15$	6.95	
(2)	$C14$	4.92; 8.05	
Mo	$A2$	3.1470	
Be_2Mo	$C14$	4.43; 7.34	
$Be_{12}Mo$	$D2b$	7.271; 4.234	25
$Be_{13}Mo$	tetr.	10.27; 4.29 ($M = 4$)	
$Be_{22}Mo$	O_h^7	11.64 }	220
$BeMo_3$	$A15$	4.89 }	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group VIa: Cr, Mo, W—*continued*			
MoTc (ω)	orthorh.	6.231; 6.500; 13.52	219
$ZrMo_2$	*C*15	7.587	26
U_2Mo (γ)	*C*11*b*	3.427; 3.279	27
W (α)	*A*2	3.1652	
Be_2W	*C*14	4.446; 7.289	
WBe_{22}	O_h^7	11.64	220
$Be_{12}W$	*D*2*b*	7.36; 4.22	
ZrW_2	*C*15	7.61	
Group VIIa: Mn, Tc, Re			
Mn (α)	*A*12	8.9126 (<742°C)	
(β)	*A*13	6.3152 (724–1 191°C)($A=20$)	28
	~*A*13	12.58 ($A=160$)	29
(γ)	*A*1	3.860	
(δ)	*A*2	3.080	30
YMn_2	*C*15	7.680 ($M=8$)	221
YMn_4	bc.tetr.	8.808; 12.521 ($M=12$)	222
YMn_{12}	*D*2*b*	8.541; 4.785	
Be_2Mn	*C*14	4.23; 6.91	
$Be_{12}Mn$	*D*2*b*	7.276; 4.256	
$GdMn_2$	*C*15	7.74	
$TiMn_2$	*C*14	4.825; 7.917	31
TiMn	*D*8*b*	8.88; 4.54	
$ZrMn_2$	*C*14	5.03; 8.22	
$ThMn_{12}$	*D*2*b*	8.74; 4.95	
Th_6Mn_{23}	*D*8*a*	12.52	
$ThMn_2$	*C*14	5.48; 8.95	
UMn_2	*C*15	7.16	
U_6Mn	*D*2*c*	10.29; 524	
VMn_4	*D*8*b*	8.92; 4.61	
$NbMn_2$	*C*14	4.87; 7.96	
$TaMn_2$	*C*14	4.86; 7.94	
$CrMn_3$	*D*8*b*	8.86; 4.59	
Tc	*A*3	2.738; 4.393	
Re	*A*3	2.7609; 4.458	
Be_2Re	*C*14	4.35; 7.09	
$Be_{22}Re$	O_h^7	11.56	
$ZrRe_2$	*C*14	5.270 1; 8.634 9	223
$HfRe_2$	*C*14	5.247 8; 8.593 4	
URe_2	orthorh.	<180°. 5.600; 9.180; 8.460	224
	*C*14	>180°. 5.433; 8.561	
Group VIII: Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt			
Fe (α)	*A*2	2.8665 (<900° and >1 400°)	
(γ)	*A*1	3.6467 (900–1 400°)	
Be_2Fe	*C*14	4.21; 6.83	
Be_5Fe	*C*15	5.88 (stable only > ~1 000°)	
Be_7Fe	hex	4.14; 10.73 ($A=18$)	
$Be_{12}Fe$	*D*2*b*	7.253; 4.232	
$CeFe_2$	*C*15	—	
Gd_2Fe_3	cubic	8.25 ($M=6$)	225
$GdFe_3$	rhomb.	4.72; 39° 46 ($M=6$)	
Gd_2Fe_7	orthorh.	5.71; 6.78; 7.15 ($M=2$)	
$GdFe_4$	hex.	5.15; 6.64 ($M=2$)	
$GdFe_5$	hex.	4.92; 4.11 ($M=1$)	
Gd_2Fe_{17}	hex.	8.39; 8.53 ($M=2$)	
$GdFe_2$	*C*15	7.391	
YFe_2	*C*15	7.357 ($M=8$)	221
$TiFe_2$	*C*14	4.77; 7.75	
TiFe	*B*2	2.976	
$TiFe_3O$	$E9_3$	11.15	32
Ti_4Fe_2O	$E9_3$	11.28	
Ti_2Fe	$E9_2$	11.31 (Duwez, Taylor)	33

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS— *continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group VIII: Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt— *continued*			
$ZrFe_2$	*C15*	7.04	
$ZrFe_2$	*C36*	4.95; 16.12	
$ThFe_5$	*D2d*	—	
U_6Fe	*D2c*	10.31; 5.24	
UFe_2	*C15*	7.065	226
VFe	*D8b*	—	
$NbFe_2$	*C14*	4.82; 7.87	
$TaFe_2$	*C14*	4.80; 7.84	
CrFe (σ)	*D8b*	8.800; 4.544	35
MoFe (σ)	*D8b*	9.188; 4.812	35
Mo_6Fe_7	$D8_5$	8.97; 30° 39′	
WFe_2	*C14*	4.73; 7.70	
W_6Fe_7	$D8_5$	9.02; 30° 31′	
$MnFe_4$	*A3*	2.53; 4.08 (not an equilibrium phase)	
Co (α)	*A3*	2.5059; 4.0659	227
(β)	*A1*	3.5447 (> 390°C)	
BeCo	*B2*	2.611	
$Be_{21}Co_5$	*A12*	7.66(?)	
$Be_{12}Co$	*D2b*	7.237; 4.249	
Be_5Co	*C15b*	5.852	
YCo_2	*C15*	7.216 ($M=8$)	221
La_3Co	DO_{11}	7.279; 10.088; 6.578 ($M=4$)	228
$Co_{13}La$	$D2_3$	7.449	
$Co_{13}La$	*D2d*	5.09; 3.94	
$CeCo_5$	*D2d*	4.96; 4.06	
Co_5Sm	*D2d*	5.004; 3.971	232
Co_2Tb	*D2d*	4.947; 3.982	
Co_5Ho	*D2d*	4.910; 3.996	
Gd_3Co	DO_{11}	5.17; 6.72; 5.94 ($M=2$)	235
GdCo	Bf	3.90; 4.87; 4.22 ($M=2$)	
Gd_2Co_3	cubic	7.98 ($M=6$)	
$GdCo_2$	*C15*	7.256	
$GdCo_3$	rhomb.	4.80; 41° 32′ ($M=6$)	
$GdCo_4$	hex.	5.47; 6.02 ($M=2$)	
$GdCo_5$	*D2d*	4.97; 3.97 ($M=1$)	
$CeCo_2$	*C15*	7.15	
$TiCo_2$	*C36*	4.72; 15.39 (Co-rich)	
	C15	6.73	
TiCo	*B2*	2.99	
Ti_4Co_2O	$E9_3$	11.30 (Rostoker[32])	
Ti_2Co	$E9_3$	11.28 (Dewez, Taylor[33])	
$ZrCo_2$	*C15*	6.89	
$ThCo_3$	*D2d*	4.95; 4.04	
UCo_2	*C15*	7.005	
UCo	*Ba*	6.36	
U_6Co	*D2c*	10.36; 5.21	
VCo_3	DO_{21}	5.032; 12.27 ($M=6$)	229
VCo	*D8b*	8.84; 4.59	
V_3Co	*A15*	4.68	
$Nb_{0.8}Co_{2.2}$	*C36*	4.73; 14.43	
$NbCo_2$	*C15*	6.75	
$Ta_{0.8}Co_{2.2}$	*C36*	4.72; 15.39	230
Co_3Ta (α)	$L1_2$	3.647 ($M=1$)	
(β)	hex.	9.411; 15.50 ($M=32$)	
Co_2Ta (α)	*C14*	4.797; 7.827	
(β)	*C15*	6.78	
(γ)	*C36*	4.700; 15.42	
~CrCo	*D8b*	8.77; 4.54	36
$Cr_{17}Co_{13}$ (σ)	*D8b*	8.81; 4.56	37
$MoCo_3$	$D0_{19}$	5.12; 4.11	
Mo_6Co_7	$D8_5$	8.98; 30° 48′	
Mo_3Co_2	*D8b*	9.229; 4.827	
WCo_3	$D0_{19}$	5.12; 4.12	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group VIII: Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt—*continued*			
W_6Co_7	$D8_5$	8.95; 30° 41′	
FeCo	*B2*	2.850 4 } transf. temp. ~730°C; constants at room temp.	
	A2	2.848 8 }	
Ni	*A1*	3.5240	
BeNi	*B2*	2.60	
$Be_{21}Ni_5$	$D8_{1.3}$	7.56	
$MgNi_2$	*C36*	4.81; 15.77	
Mg_2Ni	*Ca*	5.18; 13.19	
$CaNi_5$	*D2d*	4.95; 3.94	
YNi_2	*C15*	7.181 ($M=8$)	221
YNi_3	hex.	4.978; 24.45 }	231
YNi	orthorh.	4.10; 5.51; 7.12 ($M=4$) }	
YNi_5	*D2d*	4.883; 3.967 ($M=1$)	
$LaNi_5$	*D2d*	4.95; 4.00	
$LaNi_2$	*C15*	7.25	
$CeNi_5$	*D2d*	4.86; 4.00	
$CeNi_2$	*C15*	7.19 or 7.224	
$CeNi_3$	$D0_{21}$	4.98; 16.54	233
$PrNi_5$	*D2d*	4.94; 3.97	
$PrNi_2$	*C15*	7.19	
Gd_3Ni	$D0_{11}$	5.15; 6.70; 6.23 ($M=2$)	234
Gd_3Ni_2	tetr.	7.28; 8.61 ($M=4$)	
GdNi	*B27*	5.43; 4.35; 6.93	
$GdNi_2$	*C15*	7.208	
Gd_2Ni_7	hex.	4.937; 24.18	
$GdNi_4$	hex.	5.35; 5.83 ($M=2$)	
$GdNi_5$	*D2d*	4.90; 3.97 ($M=1$)	
Gd_2Ni_{17}	Th_2Ni_{17}	8.18; 8.47 ($M=2$)	
Ni_5Sm	*D2d*	4.924; 3.974 }	
Ni_5Tb	*D2d*	4.984; 3.966 }	232
Ni_5Ho	*D2d*	4.871; 3.966 }	
Ni_5Yb	*D2d*	4.841; 3.965	
Ti_2Ni	O_h^7–*Fd3m*	11.278 ($A=96$)	236
$TiNi_3$	$D0_{24}$	5.10; 8.31	
TiNi	*B2*	3.015	
Ti_2Ni	$E9_3$	11.29	
Ti_4Ni_2O	$E9_3$	11.30	
$ZrNi_5$	*C15b*	6.71	38
Zr_2Ni	*C16*	6.477; 5.241	238
$ZrNi_2$	*C15*	6.925	
$ZrNi_3$	$D0_{19}$	5.309; 4.303	
ZrNi	*D8b*	3.268; 9.937; 4.101	
Hf_2Ni	*C16*	6.405; 5.252	
HfNi	Bf	3.218; 9.788; 4.117	
$ThNi_5$	*D2d*	4.92; 3.99	
$ThNi_2$	*C32*	3.964; 3.852	
UNi_3	*C15*	6.783	
UNi_2	*C14*	4.97; 8.25	
U_6Ni	*D2c*	10.37; 5.21	
$PuNi_4$	monocl. 62/*m*	4.87; 8.46; 10.27; $\beta=100°$ ($M=6$)	239
$PuNi_3$	rhomb	6.22; 30° 44′ ($M=3$)	240
PuNi	Bf	3.59; 10.21; 4.22	241
VNi_3	$D0_{22}$	3.54; 7.22	
VNi_2	orh.	2.61; 3.54; 2.57	
$V_{19}Ni_{11}$	*D8b*	8.97; 4.64	
$NbNi_3$	$D0_{22}$	3.62; 7.41	
$TaNi_3$	*D0a*	5.11; 4.25; 4.54	
Cr_2Ni	*A2*(tetr. deformed)	($c/a=1.09$; metastable intermediate by quenching)	
CrNi	*D8b*	8.82; 4.58	
$MoNi_4$	*D1a*	5.72; 3.56	
$MoNi_3$	*D0a*	5.064; 4.224; 4.448	242
MoNi	*A3*	2.54; 4.18	
WNi_4	*D1a*	5.73; 3.55	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group VIII: Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt—*continued*			
$MnNi_3$	$L1_2$	3.59 (< 510°C)	
MnNi	$L1_0$	3.74; 3.52 (< ~700°C)	
	A2	2.97 (range ~700–900°C; constant at 745°)	
$FeNi_3$	Li_2	3.54 (< 586°C)	
Fe_3Cr_3Ni	cubic b.c.	8.88 (powder diagram similar *A*12-type)	
Ru	*A3*	2.705 8; 4.281 6	
	hex.	2.706 0; 4.253 7	243
Ru_2Be_3	$D5_3$	11.42	252
$RuBe_2$	*C*14	5.90; 9.10	
Ru_3Be_{10}	$D0_3$	11.03	
Ru_2Ce	*C*15	7.79	244
TiRu	*B2*	3.06	40
$ZrRu_2$	*C*14	5.13; 8.49	
URu_3	*C*12	3.980	39
RuU_2	monocl.	13.106; 3.343; 5.202; 96°9.2′ ($M=4$)	245
Rh	*A*1	3.8032	
WRh_2	*A3*	2.73; 4.38	
RhMg	*B2*	3.099	246
Rh_2Ca	*C*15	7.525	247
RhBe	*B2*	2.740	
Rh_2Sr	*C*15	7.695	
Rh_3Ti	$L1_2$	3.822	248
Rh_3Hf	$L1_2$	3.911	
Rh_3Nb	$L1_2$	3.865	
Rh_3Zr	$L1_2$	3.927	
Rh_3V	$L1_2$	3.795	
Rh_3Ta	$L1_2$	3.86	
Pd	*A*1	3.8903	
BePd	*B2*	2.819	
Be_5Pd	*C*15*b*	5.98 (ordered as Be_4Be, Pd)	
	*C*15*b*	5.98 [disordered as Be_4 (Be, Pd)$_2$]	
$BePd_{12}$	*D*2*b*	7.27; 4.25	
Pd_2Ca	*C*15	7.665	
Pd_2Sr	*C*15	7.826	247
Pd_2Ba	*C*15	7.983	
$TiPd_3$	$D0_{24}$	5.48; 8.96	
Pd_3Zr	$D0_{24}$	5.612; 9.235	248
Pd_3Hf	$D0_{24}$	5.595; 9.192	
Pd_4Th	$L1_2$	4.110	249
$PdTi_2$	*C*11*B*	3.090; 10.084	342
$PdZr_2$	*C*11*B*	3.306; 10,894	342
$PdHf_2$	*C*11*B*	3.251; 11.061	342
PdMg	*B2*	3.12	341
UPd_3	$D0_{24}$	5.757; 9.621	39
Pd_2V	f.c. tetr.	3.88; 3.72	250
Pd_3V	$D0_{22}$	3.84; 7.75	
$FePd_3$	$L1_2$	3.84	
FePd	$L1_0$	3.85; 3.72	
Os	*A3*	2.734 1; 4.391 8	
$BeOs_{12}$	monoclinic	11.31; 10.63; 8.48 96° 32′	
TiOs	*B2*	3.07	40
$ZrOs_2$	*C*14	5.18; 8.51	
UOs_2	*C*15	7.497 4	39
TaOs(σ)		9.934; 5.189	41
CrOs	*A*15	4.677	42
WOs_2 (σ)	*D*8*b*	9.686; 5.012	41
Ir	*A*1	3.8392	
Ir_2Ca	*C*15	7.545	
Ir_2Sr	*C*15	7.700	247
Ir_3Ti	$L1_2$	3.822	250
Ir_3Hf	$L1_2$	3.911	
Ir_3Nb	$L1_2$	3.865	
Ir_3Zr	$L1_2$	3.943	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group VIII: Fe, Co, Ni; Ru, Rh, Pd; Os, Ir, Pt—*continued*			
Ir_3V	$L1_2$	3.812	
Ir_3Tc	$L1_2$	3.889	
TaIr (σ)	$D8b$	9.938; 5.172	41
$ZrIr_2$	$C15$	7.346	
UIr_2	$C15$	7.4939	39
IrW	$B19$	4.452; 2.760; 4.811	
Pt	$A1$	3.9236	
$Be_{21}Pt_5$	$D8_{1-3}$ (deformed)	—	
Pt_2Ca	$C15$	7.629	
Pt_2Sr	$C15$	7.777	
Pt_2Ba	$C15$	7.920	
PtMg	$B20$	4.86	341
Pt_3Mg	$L6_0$	3.88; 3.72	341
$CePt_2$	$C15$	7.73	
$TiPt_3$	$L1_2$	3.89	
Ti_3Pt	$A15$	5.033	43
$ZrPt_3$	$D0_{24}$	5.63; 9.21	
Pt_3Hf	$D0_{24}$	5.636; 9.208	248
Pt_3U	$D0_{19}$	5.752; 4.889	39
Pt_2U	orthorh.	5.60; 9.68; 4.12	251
$FePt_3$	$L1_2$	3.88 (<700 °C)	
FePt	$L1_0$	3.86; 3.76 (<1300 °C)	
Fe_3Pt	$L1_2$	3.75 (<850 °C)	
$CoPt_3$	$L1_2$	3.831 (constant at 700 °C; transformation to disordered state ~750 °C; constant at 800 °C = 3.829)	
CoPt	$L1_0$	3.80; 3.70 (constant at 700 °C; transformation temp. to disordered $A1$-type ≈825 °C)	
NiPt	$L1_0$	3.82; 3.58 (<600 °C)	
Group Ib: Cu, Ag, Au			
Cu	$A1$	3.6146	
BeCu (γ)	$B2$	2.702	
(γ')	tetr.	2.79; 2.54 } intermediate phases during	
(γ'')	monocl.	2.54; 2.54; 3.24; 85° 25' } precipitation	
$Be_{2.4}Cu$	$C15$	5.94 (report $A2$-type with $a=2.79$) (Misch[44], Kossolapow[45]) to 5.97	
Be_3Cu	$C14$	4.179; 2.557	
ZrIr	$B2$	3.318	
Zr_2Ir	$C16$	6.51; 5.62	
$MgCu_2$	$C15$	7.03	
Mg_2Cu	Cb	5.27; 9.05; 18.21	
$CaCu_5$	$D2d$	5.10; 4.08	
$LaCu_5$	$D2d$	5.17; 4.12	
CeCu	$B27$	7.30; 4.30; 6.36	253
$CeCu_2$	orthorh, $Imma$	4.43; 7.05; 7.45	254
$CeCu_6$	orthorh. $Pnma$	8.12; 5.102; 10.162 ($M=4$)	255
$CeCu_5$	$D2d$	5.149; 4.108	
Cu_5Tb	$D2d$	4.96; 4.15 also $C15b$ 7.041	256
Cu_5Sm	$D2d$	5.074; 4.099	256
Ti_3Cu	$L1a$	4.16; 3.59	
$CuTi_2$	$C11b$	2.944; 10.786	
Ti_2Cu	$E9_3$	11.24	
Ti_4Cu_2O	$E9_3$	11.47	
TiCu (δ)	$L2a$	4.44; 2.86	
(γ)	$B11$	3.11; 5.89	
$TiCu_3$ (β)	Ae	2.59; 4.53; 4.35 (> ~600 °C)	
(β)	$D0a$	5.15; 4.34; 4.52 (< ~600 °C)	
$CuZr_2$	$C11B$	3.2204; 11.1832	342
Zr_3Cu	$L1a$	4.54; 3.72	
$CuHf_2$	$C11B$	3.1695; 11.1333	342
$ThCu_2$	$C32$	4.35; 3.47	47
Th_2Cu	$C16$	7.28; 5.74	47
UCu_5	$C15b$	7.03	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group Ib: Cu, Ag, Au—*continued*			
$FeNi_3Cu_6$	tetr.	3.584; 3.548 (a phase of said composition decomposes into the Cu-poor tetr. intermediate phase + Cu-rich cubic phase with $a=3.592$. In the final state 2 cubic phases coexist with $a=3.592$ and $a=3.568$)	
$FeNi_3Cu_3$	tetr.	3.577; 3.598 (a phase of said composition decomposes into the Cu-rich tetr. intermediate phase + a Cu-poor cubic phase with 3.567. In the final state two cubic phases coexist with $a=3.590+3.567$)	
$PdCu_3$	$L1_2$	3.65	
	tetr.	9.74; 7.31 (quenched 460 °C)	
PdCu	$B2$	2.96	
$PtCu_3$	$L1_2$	3.68	
PtCu	$L1_1$	7.58; 90° 54′	
Pt_3Cu	$L1b$	3.849	
Ag	$A1$	4.0853	
LiAg	$B2$	3.17	
Li_3Ag	$D8_{1-3}$	9.602	
Be_2Ag	$C15$	6.30	
MgAg	$B2$	3.314	
Mg_3Ag	hex.	4.88; 7.79	
$CuAg_2$	$C14$	5.72; 9.35 (trace Mg or Ag)	
Ca_5Ag_3	tetr.D–8_1	8.039; 15.011	258
LaAg	$B2$	3.814	
CeAg	$B2$	3.746	
PrAg	$B2$	3.739	
TiAg	$L1_0$	4.10; 4.07	
ZrAg	$L1_0$	—	
$AgZr_2$	$C11B$	3.2464; 12.0037	342
Th_2Ag	$C16$	7.56; 5.84	48
$PtAg_3$	$L1_2$	3.88 (<800°C); $A1$ 3.91>800°C	
Pt_3Ag	$L1_2$	3.90	
Au	$A1$	4.0789	
$NaAu_2$	$C15$	7.803	
Na_2Au	$C16$	7.40; 5.51	
BeAu	$B20$	4.67	
Be_3Au	$C15b$	6.097	
MgAu	$B2$	3.266	
Mg_3Au	$D0_{18}$	4.63; 8.44	
$TiAu_4$	$D1a$	6.485; 4.002	
$TiAu_2$	$A3$	2.79; 4.77	
Ti_3Au	$L1_2$	4.096	
Ti_3Au	$A15$	5.097	43
Th_2Au	$C16$	7.462; 5.989	48
V_3Au	$A15$	4.88	49
Nb_3Au	$A15$	5.21	49
MnAu	$B2$	3.256	
Au_2Mn	$C11b$	3.363, 8.592	259
Au_4Mn	$D1a$	6.45; 4.03	260
$PtAu_3$	$L1_2$	3.926 1	
CuAu	$L1_0$	3.98; 3.72	
	$L1_0$ (orthorh. deformed)	($c/a=1.003$)	
Cu_3Au	$L1_2$	3.7474 a (disordered) = 3.752 8	
Group IIb: Zn, Cd, Hg			
Zn	$A3$	2.665 0; 4.947 0	
$LiZn_4$	$A3$	2.78; 4.39	
Li_3Zn_7	Ck	4.36; 2.51	
LiZn	$B32$	6.21	
$NaZn_{13}$	$D2_3$	12.28	
KZn_{13}	$D2_3$	12.36	
Mg_2Zn_{11}	$D8c$	8.55	
$MgZn_2$	$C14$	5.21; 8.54	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIb: Zn, Cd, Hg—*continued*			
$CaZn_{13}$	$D2_2$	12.13	
$CaZn_5$	$D2d$	5.40; 4.22	
$SrZn_5$	orthorh. *Pmcn*	5.32; 6.72; 13.15 ($M=4$)	50
$SrZn_5$	$D2d$	5.549; 4.283	
$SrZn_{13}$	$D2_3$	12.22	
$BaZn_5$	orthorh. *Amam*	5.32; 8.44; 10.78 ($M=4$)	50
$BaZn_{13}$	$D2_3$	12.33	
$LaZn_5$	$D2d$	5.43; 4.23	
LaZn	$B2$	3.75	
CeZn	$B2$	3.70	
PrZn	$B2$	3.67	
$TiZn_3$	$L1_2$	3.932 2	51
$TiZn_2$	$C14$	5.064; 8.210	51
TiZn	$B2$	3.143	
Th_2Zn	$C16$	7.62; 5.64	47, 52
$ThZn_2$	$C32$	4.497; 3.718	261
$ThZn_4$	$D13$	4.273; 10.59	261
$ThZn_9$	$D2d$	5.24; 4.45	52
Th_4Zn_7	$D1_3$	9.03; 13.20	52
Th–Zn			
(x phase)	cybic f.c.	5.68	52
$ZrZn_{22}$	f.c.c.*Fd*/3*m*	14.11	262
$ZrZn_6$	orthorh.	17.8; 12.5; 8.68	262
Zr_3Zn_2	tetr.$P4_2mm$	7.633; 6.965	263
$NbZn_2$	$C36$	5.05; 16.32	264
$CrZn_{11}$	hex.	12.9; 30.5	
$MnZn_{13}$ (ξ)	monocl.	13.7; 7.6; 5.1; 128° 44′	
$MnZn_9$ (δ_1)	hex.	12.8; 57.6	
Mn_5Zn_{21} (Γ)	$D8_{1-3}$	9.14	
$MnZn_3$(α)	$L1_2$	3.85 (<320°C)	
~$MnZn_2$(ε)	$A3$	2.75; 4.44 (>350°C)	
~MnZn (β)	$A2$	3.05(high temp.)	
(β_1)	$A13$	(low temp.)	
$FeZn_{13}$(ξ)	monocl.	13.65; 7.61; 5.1; 128° 44′ ($A\approx28$)	
$FeZn_{10}$	hex.	12.8; 57.6 ($A\approx555$)	
Fe_5Zn_{21}	$D8_{1-3}$	8.98	
$CoZn_{13}$ (ξ)	monocl.	13.46; 7.49; 5.06; 127° 05′	
Co_5Zn_{21}	$D8_{1-3}$	8.92	
CoZn(β_1)	$A13$	6.33	
(β)	$A2$(?)	(>920°C)	
Ni_5Zn_{21}	$D8_{1-3}$	8.90	
NiZn(β_1)	$L1_0$	2.73; 3.19 (high temp.)	
(β)	$B2$	2.91	
NiMgZn	$C15$	6.96	
Rh_5Zn_{21}	$D8_{1-3}$	—	
Pd_2Zn	$C37^1$ type	5.35; 7.65; 4.14	341
$PdZn_{11}$ (η)	similar to $A3$	$c/a\approx1.55$	
$Pd_{18}Zn_{82}$ (γ)	similar to $D8_{1-3}$	9.09	γ is more similar to γ-brass-str. than γ^1
$Pd_{22}Zn_{78}$ (γ^1)	similar to $D8_{1-3}$	—	
Pd_2Zn_3 (β_1)	$B2$	3.04 (> ~600°C)	
PdZn(β)	$L1_0$	4.14; 3.50	53
Pd_2Zn	$B2$	3.05 (> ~600°C)	
Pt_5Zn_{22} (γ)	$D8_{1-3}$	18.08	
~$PtZn_3$ (γ_1)	similar to $D8_{1-3}$		
$PtZn_2$ (ξ)	$C32$	4.10; 2.74	
PtZn(ξ)	$L1_0$	4.03; 3.47	
Pt_3Zn	$L1_2$	3.89 (<≈800°C)	
$CuZn_5$ (ε)	$A3$	2.75; 4.29	
$CuZn_3$ (δ)	$A2$	3.01 (stable between 550–700°C)	
Cu_5Zn_8 (γ)	$D8_2$	8.84	
CuZn(β)	$A2$	(>450°C) 2.95	
(β')	$B2$	(<~450°C) 2.94	
~Cu_6Zn_4	tetr. f.c.	3.678; 3.602 (intermediate state during precipitation α from β at 225°C)	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIb: Zn, Cd, Hg—*continued*			
$\sim Cu_6Zn_4$	tetr. f.c.	3.690; 3.650 (intermediate state during precipitation α from β at 250 °C)	
Cu_2TiZn	*CsCl* (B2) type	2.95	265
	tetr. b.c.	2.945; 3.007 (intermediate state during precipitation α from β at 250 °C)	
$AgZn_3$	*A*3	2.81; 4.42	
Ag_5Zn_8	$D8_2$	9.340 7	54
AgZn (β)	*A*2	3.16 (high temp.)	
(β′)	*B*2	3.16 (medium temp.)	
(ξ)	*Bb*	7.64; 2.82 (<260 °C)	
$(Ag_{0.07}Zn_{0.93})_2Mg$	*C*36	5.21; 3.440	
$(Ag_{0.10}Zn_{0.90})_2Mg$	*C*36	5.21; 9.03	
$(Ag_{0.25}Zn_{0.75})_2Mg$	*C*36	5.24; 17.27	
$(Ag_{0.4}Zn_{0.6})_2Mg$	*C*15	7.46	
$AuZr_2$	*C*11*B*	3.28; 11.6	342
$AuHf_2$	*C*11*B*	3.230 9; 11.605 7	342
AuZn (ε)	*A*3	2.81; 4.37	
$AuZn_3$	*cub* O_h^3 *Pm*3*n*	7.887	266
$Au_{23}Zn_{77}$	cubic	11.2 ($A \approx 90$)	
Au_3Zn_3	$D8_{1-3}$	9.25	
AuZn	*B*2	3.12	
Au_3Zn (α)	*A*1	4.031 (>420 °C; quenchable)	
(α′)	tetr.	4.026; 4.107 (between 270–415 °C; not quenchable)	
(α″)	*L*1*c*	3.948; 8.306 (<260 °C)	
Cd	*A*3	2.979 3; 5.619 6	
$LiCd_3$	*A*3	3.08; 4.89	
LiCd	*B*32	6.69	
Li_3Cd	*A*1	4.25	
KCd_{13}	$D2_3$	13.78	
$RbCd_{13}$	$D2_3$	13.88	
$CsCd_{13}$	$D2_3$	13.89	
$MgCd_3$	$D0_{19}$	6.2; 5.1	
MgCd	*B*19	5.00; 3.22; 5.27	
Mg_3Cd	$D0_{19}$	6.26; 5.07 (<160 °C)	
$CaCd_2$	*C*14	5.98; 9.64	
SrCd	*B*2	4.003	55
BaCd	*B*2	4.207	55
$BaCd_{11}$	tetr.	12.02; 7.74 ($M=4$)	56
LaCd	*B*2	3.90	
CeCd	*B*2	3.86	
PrCd	*B*2	3.82	
TiCd	*B*11	2.904; 8.954 ($M=4$)	267
Ti_2Cd	*C*11	2.865; 13.42 ($M=6$)	267
$ZrCd_2$	cubic f.c.	4.376 8	51
ZrCd	*B*11	3.124 3; 8.75	51
$NaCd_2$	O_h^7	3.056	268
Ni_5Cd_{21}	$D8_{1-3}$	9.76	
$Pd_{17.5}Cd_{82.5}$ (γ)	$D8_{1-3}$	9.94	
$Pd_{22}Cd_{78}$ (γ_2)	$\sim D8_{1-3}$	9.92	
Pd_2Cd_2	A_2	3.25 (ordered?)	
PdCd	$L1_0$	4.31; 3.65	53
$\sim PtCd_5$ (γ)	$D8_{1.3}$	9.88	
$PtCd_2$ (ξ)	$L1_0$	4.174; 3.186	
PtCd	$L1_0$	4.24; 3.91	53
Cu_5Cd_3	$D8_2$	9.62	
$AgCd_3$	*A*3	3.07; 4.81	
Ag_5Cd_3	$D8_{1-3}$	9.96	
AgCd	*A*3	2.917 0; 4.827 9 at 25°C	269

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIb: Zn, Cd, Hg—*continued*			
AgCd (β)	*A2*	(>443°C) 3.32	
(β_1)	*A3*	(186–475°C) 2.98; 4.81	
(β')	*B2*	(<210°C) 3.33	
$AuCd_3$	$D0_{21}$	8.1667; 8.511	
Au_2Cd	*A3*	2.919; 4.405	
AuCd (β_1)	*B2*	3.33 (>60–80°C)	
(β^1)	*B19*	3.15; 4.85; 4.75 (<~60°C)	
Au_2Cd (α_2)	*A3*	2.91; 4.79	
Au_3Cd (α_1)	$L1_0$	4.116; 4.131 (<~400°C)	
ZnCuCd	*C15*	7.15	
Hg	*A10*	2.9925; 70° 44.6′ (78 K): 2.9863; 70° 44.6′ (5 K)	59
$LiHg_3$	$D0_{19}$	6.24; 4.79	
LiHg	*B2*	3.23	
Li_3Hg	$D0_3$	6.55	
NaHg	orthorh.	7.19; 10.79; 5.21 ($M=8$)	60
Na_3Hg_2	tetr.	8.52; 7.80 ($M=4$)	60
$NaHg_2$	*C32*	5.029; 3.230 ($M=1$)	60
KHg	triclinic	6.59; 6.76; 7.06 ($\alpha=106°$ 5′, $\beta=101°$ 52′; $\gamma=92°$ 47′)	61, 62
K_5Hg_7	orthorh. *Pbcm*	10.06; 19.45; 8.34 ($M=4$)	270
KHg_2	orthorh.	8.10; 5.16; 8.77 ($M=4$)	61, 62
$MgHg_2$	*C11*	3.83; 8.78	
MgHg	*B2*	3.44	
Mg_5Hg_3	$D8_8$	8.24; 5.92	
Mg_3Hg	$D0_{18}$	4.86; 8.64	
SrHg	*B2*	3.922	55
BaHg	*B2*	4.125	55
$BaHg_{11}$	*D2e*	9.60	
$LaHg_4$	cubic	10.97 ($A=54$; similar to $D8_{1-3}$-type)	
$LaHg_3$	$D0_{19}$	682; 4.95 (cf. UHg_2)	
$LaHg_2$	*C32*	4.95; 3.63	
LaHg	*A2*	3.84 (ordered as *B2*-type?)	
CeHg	*A2*	3.81 (ordered as *B2*-type?)	
PrHg	*A2*	3.79 (ordered as *B2*-type?)	
TiHg	$L1_0$	3.009; 4.041	51
Ti_3Hg	*A15*	5.1888	51
	$L1_2$	4.1654 ($A=4$)	51
Hg_3Th	*A3*	3.361; 4.905	271
HgTh	f.c.c.	4.80	
ZrHg	$L1_0$	3.15	51
$ZrHg_3$	*A15*	5.5583	51
Zr_3Hg	$L1_2$	4.3652	51
$ThHg_3$	*A3*	3.38; 4.72	47
$ThAg_3$	*A3*	3.361; 4.905	272
ThAg	f.c.c.	4.80	272
NdHg	*A2*	3.77 (ordered as *B2*-type)	
UHg_4	cubic b.c.	3.63 (with superstructure lines)	
UHg_3	*A3*	3.33; 4.89	
UHg_2	*C32*	4.99; 4.89	
$NiHg_4$	hex.	6.016	
PdHg	$L1_0$	4.28; 3.69	
Pt_3Hg	*A1*	3.92	341
~CuHg	$D8_{1-3}$	9.41	
Ag_3Hg_4	$D8_{1-3}$	10.02	
$Ag_{5.5}Hg_{4.5}$	*A3*	2.99; 4.85	
Au_3Hg	*A3*	2.91; 4.78	
$\sim Zn_3Hg_3$	hex.	2.71; 5.48	
CdHg	*A6*	3.885; $c/a=0.747$ at 31% Hg	63
$CdHg_2$	*C11b*	3.98; $c/a=0.721$ at 71.8% Hg	63
CdHg (β)	hex.	3.2062; 2.9856	64
Group IIIb; Al, Ga, In, Tl			
Al	*A1*	4.0488	
LiAl	*B32*	6.3685	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIIb; Al, Ga, In, Tl—*continued*			
Mg_2Al_3 (β)	$Fd3m$	28.239 ($A = 1\,172$)	
~MgAl (δ')	$A12$ (deformed)		
(δ)	$A12$	10.543 8	
γMgAl	$A12$	10.57 (38.5 at.% Al): 10.488 (48.4 at.% Al)	65
$Mg_{32}Al_{49}$	$D8c$	1416	
$Al_{18}Mg_3Cr_2$	O_h^7Fd3m	14.562 a/cell 184	273
Y_3Al_2	tetr.	8.239; 7.648 ($M = 4$)	274
YAl	$B27$	3.884; 11.522; 4.385 ($M = 4$)	
YaI	$B2$	3.754	
$CaAl_4$	$D1_3$	4.35; 11.07	
$CaAl_2$	$C15$	8.038	
SrAl	cubic b.c.	15.8 ($A = 116$)	
$SrAl_4$	$D1_3$	4.463; 11·203	
$BaAl_4$	$D1_3$	4.566; 11.250	66
$LaAl_4$	$D1_3$	4.42; 10.21	
$LaAl_2$	$C15$	8.148	
CeAl	orthorh.	9.27; 7.68; 5.76	67
$CeAl_4$	$D1_3$	4.374; 10.12	
$CeAl_2$	$C15$	8.06	
Ce_3Al (α)	$A3$	7.04; 5.451	67
Ce_3Al (β)	$L1_2$	4.985	67
NdAl	$B2$	3.73	
$TiAl_3$	$D0_{22}$	3.848; 8.596	
$TiAl_3$	$D0_{19}$	5.775; 4.638	68
Ti–Al (α_2)	hex.	5.76; 4.65	60
TiAl	$L1_0$	3.99; 4.07	
Al_6Ti	isom. with $MnAl_{16}$	6.58; 7.63; 9.00	275
Ti_3Al	$D0_{19}$ struct.	5.77; 4.62	276
$ZrAl_3$	$D0_{23}$	4.014; 17.320	
Zr_3Al	$L1_2$	4.372	82
Zr_2Al	hex. Pb_3mmc	4.893 9; 5.928 3	277
Zr_2Al_3	orthorh. $Fdd2$	9.601; 13.906; 5.574	278
Zr_4Al_3	hex. C_{3h}^1–P_6^1	5.433; 5.390 ($M = 1$)	279
Zr_3Al_2	tetr. D_{4h}^{14}–P_2^4/mnm	7.630; 6.998	280
HfAl	orthorh. $Cmcm$	3.25; 10.83; 4.28 ($M = 4$)	281
Hf_2Al_3	orthorh.	9.52; 13.76; 5.52 ($M = 8$)	282
$ThAl_3$	DO_{19}	6.500; 4.626	48
$ThAl_2$	$C32$	4.388; 4.162	48
Th_3Al_2	tetr. $P4/mbm$	8.125; 4.217	48
Th_2Al	$C16$	7.614; 5.857	48
UAl_4	$D1b$	4.41; 6.27; 13.71	
UAl_3	$L1_2$	4.265 1	
UAl_2	$C15$	7.766	
$NpAl_2$	$C15$	7.785	70
$NpAl_3$	$L1_1$	4.262	70
$NpAl_4$	$D1b$	4.42; 6.26; 13.71	70
$PuAl_3$	hex.	6.10; 14.47 ($M = 6$)	81
VAl_3	$D0_{22}$	3.780; 8.321	
C_4Al_{23}	hex. $P6_3/mmc$	7.693; 17.04	71
$NbAl_3$	$D0_{22}$	3.844; 8.605	
Nb_2Al	tetr.	9.943; 5.586 30 a/cell	283
Nb_3Al	O_h^3–$Pm3n$	5.187 ($M = 2$)	337
$TaAl_3$	$D0_{22}$	3.839; 8.535	
$CrAl_7$	orthorh.	19.99; 34.51; 12.47	72
	monocl.	20.43; 7.62; 25.31; 155° 10	73
	orthorh.	24.8; 24.7; 30.2 ($M = 145$)	74
Cr_2Al_{11}	orthorh.	24.8; 24.7; 30.2 ($M = 93$)	74 (*cf.* 72)
Cr_5Al_8	$D8_{10}$	7.79; 109° 8′	
Cr_2Al	$C11$	3.005; 8.648	
$CrMg_{1.5}Al_{12}$	cubic f.c.	14.65	75
$CrMg_2Al_{12}$	cubic	14.68 ($M = 16$)	
$Cr_2Mg_3Al_{18}$ (E phase)	$Fd3m$	14.562	76

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIIb: Al, Ga, In, Tl—*continued*			
$MoAl_{12}$	b.c.c.	7.581 5	284
$MoAl_7$	monocl.	5.12; 13.0; 13.5 ($\beta = 95°$)	284
WAl_4	monocl.	5.272; 17.771; 5.218; 100° 12′ (a/cell = 30)	285
Mo_3Al	monocl.	4.950	
WAl_5	hex. $P6_3$	4.902 0; 8.857 0	78
WAl_{12}	cubic b.c., $Im3$	7.5803	77
$MNAl_6$	orthorh.	6.497 8; 7,551 8; 8.870 3	79
$MnAl_4$	hex.	28.41; 12.38	
MnAl (y)	orthorh.	14.79; 12.60; 12.43	
(x)	monocl. or tricl.	$a \approx b \approx 5.1$	
Mn_3Al_{10}	hex.6/*mmm*	7.543; 7.898	287
Mn_4Al_{11}	tricl.	5.092; 8.862; 5.047; α 85° 19′; β 100° 24′; γ 105° 20′	286
$MnAl_3$	orthorh.*Pnma*	14.79; 12.42; 12.59 ($M = 36$)	288
$(Mn, Cr)Al_{12}$	cubic b.c., Im^3	7.507	77
$(Mn, Si)_2Al_6$	similar to $D8_{11}$	—	
Tc_2Al_3	trigonal	4.16; 5.13	289
$TcAl_{12}$	b.c.c. (WAl_{12})	7.525 5	289
$TcAl_4$	monocl.	5.1; 17.0; 5.1 ($\beta = 100°$)	289
$ReAl_6$	isomorph with $MnAl_6$	6.59; 7.61; 9.02	275
$ReAl_{12}$	WAl_{12}	7.527	
Fe_2Al_7 (λ_1)	rhomb. (?)	—	
Fe_2Al_5	$D8_{11}$	7.660; 6.390; 4.195	80
$FeAl_2$ (ν)	monocl. (?)	—	
$FeAl_3$	D_{2h}^{23}	47.43; 14.46; 8.08 ($A = 400$)	
FeAl (β_2)	*B*2	2.909	
Fe_3Al (B_1)	$D0_3$	5.792 3	
$Fe_2Al + Co_{0.5}$	$L'1_2$	3.75	
Co_2Al_9	*D*8*d*	8.56; 6.29; 6.21; 94° 45′	
Co_2Al_5	$D8_{11}$	7.608; 7.672	
CoAl	*B*2	2.861 1	
$NiAl_3$	$D0_{20}$	6.60; 7.35; 4.80	
Ni_2Al_3	$D5_{13}$	4.03; 4.89	
NiAl	*B*2	2.886 4	
Ni_3Al	$L1_2$	3.5655	
Ni_2TiAl	$L2_1$	5.843	
$NiFe_2Al$ (β′)	*B*2	≈ (Ni, Fe) (Al, Fe)	
$NiFeAl_9$	*D*8*d*	8.598; 6.271; 6.207; 94° 39′	87
$\sim NiFe_2Al_9$	*D*8*d*		88
RuAl	*cub.*	3.03	290
$RuAl_2$	*C*11*a*	4.40; 6.38	
$RuAl_3$	$D0_{24}$	4.81; 7.84	
Pd_2Al_3	$D15_{13}$	4.21; 5.15	
PdAl	monoc.	9.68; 15.14; 5.24; 78° 54′	83
	*B*2	3.049 (> 700°C)	
OsAl	*B*2	3.001	83
IrAl	*B*2	2.977	83
PrAl	*B*20	4.866	83
$PtAl_2$	*C*1	5.91	
Pt_5Al_3	D_{2h}^9	5.41; 10.70; 3.95 ($M = 2$)	338
RhAl	*B*2	2.968	
Rh_2Al_5	$D8_{11}$	7.893; 7.854	
Rh_2Al_9	*D*8*d*	8.721; 6.428; 6.352; 94° 48′	
Pt_3Al	Au_3Cu type	3.876	
$CuAl_2$	*C*16	6.063; 4.872 (stable form)	
	tetr.	8.2; 11.6 (metastable form, *e.g.* precipitated from supersaturated solid solution)	
	*C*1 (deformed into tetr.)	$a = 5.71$; $c/a = 1.017$ (metastable)	
CuAl (η)	orthorh.	6.88; 4.08; 9.87 (49–50 at. % *Al*; similar to $-D5_{13}$)	
Cu_4Al_3 (ζ)	monocl.	7.06; 4.04; 10.00; 90° 38′ (42–43 at. % *Al*; similar to $-D5_{13}$)	
Cu_3Al_2 (γ_2)	$D8_{1-3}$	8.69 ($A = 50.5$ to 49.5; 38–41 at. % *Al*)	
$Cu_{32}Al_{19}$ (γ_1)	$\sim D8_{1-3}$	~8.71 ($A = 51$ for pseudo-cubic cell: monocl.)	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIIb; Al, Ga, In, Tl–*continued*			
Cu_9Al_4 (γ)	$D8_3$	8.685 to 8.704 ($A = 52.2$ to 51.8; 31–35 at. % Al)	
Cu_2Al	$A3$	2.60; 4.22 (Kurdjumow's martensitic γ'-phase)	
	$\sim A3$, $D2_h^{13}$	4.51; 5.20; 4.22	
Cu_3Al (β)	$A2$	(> 570 °C) 2.94	
(β_1)	$D0_2$	(~ 300 °C) 5.84 (unstable)	
(β')	$\sim A1$ (?)	(< 300 °C)	
$\sim Mg_4CuAl_6$	$D8e$	14.35	
$\sim Mg_2Cu_6Al_5$	$D8c$	8.31	
$\sim MgCuAl_2$	$E1a$	4.00; 9.23; 7.14	
$Mg_6Cu_3Al_7$	cubic b.c.	12.09 ($A = 94$)	
$Mg_2Cu_2Al_5$	tetr.	5.71; 7.94	
$MgCu_{0.9}Al_{1.1}$	$C36$	5.098; 16.64	
MgCuAl	$C14$	5.09; 8.40	
Mn_2CuAl_{12}	orthorh.	7.96; 24.06; 12.48 (Phragmén[89]; identical work with $Cu_3Mn_3Al_{20}$ Raynor; r-AlCuMn Petri; and $MnCuAl_6$ Hanemann's 'T'; references *see* Phragmén[89])	
$\sim Mn_3CuAl_{12}$	orthorh.	14.79; 12.60; 12.43 (Hanemann's 'Y')	89
(Mn, Cu)Al (δ)	$B2$	—	
$(Mn, Cu)_3Al$ (β)	$D0_3$	5.9	
$MnCu_2Al$ (β')	$L2_1$	5.95	
$FeCu_{10}Al_{10}$ (ζ)	monocl. (?)	(similar to $D15_{13}$)	
$FeCu_{10}Al_{18}$ (χ)	monocl. (?)	(similar to $D15_{13}$)	
$FeCu_2Al_7$	$E9a$	6.32; 14.78	
(Fe, Cu)			
$(Cu, Al)_6$	orthorh.	6.43; 7.45; 8.77 (isom. $MnAl_6$)	
$NiCu_3Al_6$	$B2$ (deformed) isom. with $ZnCu_3Al_3$	—	
$\sim NiCu_4Al_7$	rhomb.	4.105; 39.97	84
(T-phases)	cubic	14.6	84
Ag_2Al (γ)	$A3$	2.90; 4.71	
Ag_3Al (β')	$A13$	6.92	
(β)	$A2$	3.24	
$Ca(Ag, Al)_2$	$C14$	—	
$AuAl_2$	$C1$	5.997 3	
$\sim Au_3Al$	$D8_{1-3}$ (deformed)	(hex.?)	
$\sim Au_4Al$	$A13$	6.920 8	
Zn_3Al_2	$L1_2$ (?)	4.04	
$Mg_{32}(Zn, Al)_{49}$	$D8e$	14.2	
$\sim ZnCu_2Al$ (T)	$A2$	2.92	
$\sim ZnCu_3Al_3$ (T')	$B2$ (deformed) isom. with $NiCu_3Al_6$	—	
Ga	$A11$	4.518 6; 7.652 0; 4.525 8	
LiGa	$B32$	6.20	
Mg_5Ga_2	$D8g$	13.72; 7.02; 6.02	
Mg_2Ga	$C22$	7.85; 6.94	
$CaGa_2$	$C32$	4.31; 4.31	
$LaGa_2$	$C32$	4.32; 4.40	
$CeGa_2$	$C32$	4.30; 4.31	
$PrGa_2$	$C32$	4.28; 4.28	
α_2GaTi_3	$D0_{19}$	5.74; 4.63	291
TiGa (α_2)	$D0_{19}$	5.76; 4.64	85
Ti_2Ga	$B8_2$	4.51; 5.50	86
$TiGa_3$	$D0_{22}$	5.55; 8.09	
$ZrGa_3$	$D0_{22}$	5.61; 8.71	
Zr_5Ga_3	$D8_8$	8.04; 5.71	291
Nb_3Ga	$A15$	5.171	337

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIIb: Al, Ga, In, Tl—*continued*			
V_3Ga	*A*15	4.816	337
Mo_3Ga	*A*15	4.932	
CoGa	*B*2	2.86	83
$NiGa_4$	*D*8*f*	8.41	
Ni_2Ga_3	$D5_{13}$	4.05; 4.89	
NiGa	*B*2	2.87	
Ni_3Ga_2	*B*8	4.052; 4.387	
Ni_2Ga	*B*8	3.99; 4.97	
	*A*6	3.75; 3.38	
RhGa	*B*2	3.01	
PdGa	*B*20	4.88	
$PtGa_2$	*C*1	5.91	
Pt_2Ga_3	$D5_{13}$	4.22; 5.17	
PtGa	*B*20	4.90	
Pt_4Ga	monocl.	7.74; 7.74; 7.785 ~ 90°	293
Pt_3Ga	$L1_2$	3.892	
Pt_5Ga_3	orthorh.	8.031; 3.94; 7.44	
$PtGa_6$	orthorh.	15.946; 12.034; 8.87	
$CuGa_2$ (θ)	*C*38	2.83; 5.84 ($A=3$)	
~Cu_9Ga_4 (γ)	$D8_{1-3}$	8.71 (between 500 and 836 °C; 29–35% Ga; $A=52$; electrons/cell = 85; disordered)	
(γ_1)	$D8_{1-3}$	8.71 (< 645 °C; 30–37% Ga; $A=52$; electrons/cell = 86; ordered)	
(γ_2)	$D8_{1-2}$	8.70 (< 485 °C; 33–37% Ga; $A=49$; electrons/cell = 86)	
(γ_3)	$D8_{1-3}$	8.65 (< 468 °C; 37–43% Ga; $A=47$; electrons/cell = 86)	
Cu_4Ga	*A*3	2.59; 4.23	
Ag_3Ga (γ)	*D*0*b*	7.80; 288 (< ~440 °C)	
(β)	*A*3	2.93; 4.75 (> ~440 °C)	
$AuGa_2$	*C*1	6.06	
AuGa	*B*31	6.38; 6.25; 3.41	
In	*A*6	3.253; 4.947 0	
LiIn	*B*32	6.79	
NaIn	*B*32	7.30	
$MgIn_2$	$L1_2$	4.60	
~MgIn (β'')	$L1_0$	3.24; 4.38 (< ~300 °C)	
~$Mg_{70}In_{30}$ (β')	$L1_2$	(< ~300 °C)	
β-Mg–In	*A*1	(> ~300 °C; ranging from ~20–50 at. % In)	
~MgIn (β''')	orthorh.	(at ~300 °C, between B'' and β; $b/a \approx 1$)	
Mg_2In	*C*22	8.27; 3.42 (< 300 °C)	
α_2Ti_3In	$D0_{19}$	5.89; 4.76	291
Mn_3In	$D8_{1-3}$	9.44	
ZrIn	$L1_2$	4.461	291
$ThIn_3$	$L1_2$	4.695	292
~$NiIn_3$ (η)	*D*8*f*	9.18	
Ni_2In_3 (δ')	$D5_{13}$	4.39; 5.30	
NiIn (δ)	*B*2	3.09 (> 760 °C)	
(ε)	*B*35	4.54; 4.34 (< 840 °C; constant after Hellner[90]; Makarow[91] has $a=5.20$; $c=4.34$)	
Ni_2In (β)	*B*8	4.19; 5.15	
Ni_3In (γ)	$D0_{19}$	5.32; 4.24	
~$PdIn_3$	*D*8*f*	9.42	
Pd_2In_3	$D5_{13}$	4.52; 5.49	
PdIn	*B*2	3.25	
Pd_3In	*A*6	4.06; 3.79	
Pt_3In_7	*D*8*f*	9.42	
$PtIn_2$	*C*1	6.35	
Pt_3In	$L1_0$	3.93; 3.87	342
Pt_2In_3	$D5_{13}$	4.53; 5.51	
Cu_3In	$B8_2$	4.28; 5.25	
~Cu_7In_3 (γ)	$D8_{1-3}$	9.24 (> 610 °C)	
(δ)	tetr. (?)	8.97; 9.14 (< 630 °C; constants and symmetry derived by powder method Reynolds[92]; structure is said to be similar to $D8_{1-3}$-type. Similarity to *B*8-type was proposed by Hellner[93])	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IIIb; Al, Ga, In, Tl—*continued*			
Cu_4In	*A2*	3.046	
Cu_2MnIn	$L2_1$	6.187	
AuIn	c.c. pseudo orthorh.	4.29; 10.57; 3.55 (α 90.54°; β 90.00°; γ 90.17°)	80
Au_3In	$L6_0$	5.872; 4.735; 5.150	
CdIn (β)	hex.	3.211 2; 2.992 8	64
Tl	*A3*	3.456 6; 5.524 8 (<230°C)	
	A2	3.879 (>230°C)	
LiTl	*B2*	3.42	
NaTl	*B32*	7.47	
MgTl	*B2*	3.63	
Mg_2Tl	*C22*	8.11; 7.34	
Mg_5Tl_2	*D8g*	15.17; 7.30; 6.16	
$CaTl_3$	$L1_2$	4.79	
CaTl	*B2*	3.85	
SrTl	*B2*	4.02	
$LaTl_3$	*A3*	3.45; 5.52	
LaTl	*B2*	3.91	
CeTl	*B2*	3.89	
$ThTl_3$	$L1_2$	4.748	292
PrTl	*B2*	3.86	
Pd_2Tl	*B8*	—	
Pd_3Tl	$L6_0$	4.12; 3.84	342
PtTl	*B35*	5.61; 4.64	
$\sim HgTl_8$	*A2*	3.82	
$\sim Hg_5Tl_2$	*A1*	4.66 (perhaps with superstructure)	
$HgLi_2Tl$	*B2*	3.35	
In_3Tl	*A2*	3.81	
Group IVb: Si, Ge, Sn, Pb			
Si	*A4*	5.430 6	
$NaSi_2$	tetr.	4.98; 16.7	
Mg_2Si	*C1*	6.34	
$CaSi_2$	*C12*	10.4; 20° 30′	
CaSi	B_c	3.91; 4.59; 10.80	102
Ca_2Si	*C23*	7.667; 4.799; 9.002	
$BaSi_1$	*C32*	4.38; 4.82	294
$LaSi_2$	*Cc*	4.27; 13.72	
$CeSi_2$	*Cc*	4.14; 13.81	
$PrSi_2$	*Cc*	4.14; 13.64	
$NdSi_2$	*Cc*	4.10; 13.53	
$SmSi_2$	*Cc*	4.04; 13.33	
YSi	*Bf*	4.25; 10.52; 3.82 ($M=4$)	295
YSi_2	*C42*	4.05; 3.95; 13.22	
TiSi	*B27*	6.544; 3.638; 4.997	296
$TiSi_2$	*C49*	3.6; 13.76; 3.60	94
Ti_5Si_3	$D8_8$	7.47; 5.16	
Zr_2Si	*C16*	6.56; 5.36	95, 96
Zr_5Si_3	*C16*	7.87; 5.54	95
$ZrSi_2$	*C49*	3.72; 14.69; 3.66	94
$HfSi_2$	*C49*	3.69; 14.46; 3.64	94
$ThSi_2$	*Cc*	4.13; 14.35	
USi_2 (α)	*Cc*	3.97; 13.71 } Zachariasen[97]	
(β)	*C32*	3.85; 4.06 }	
USi	*B27*	5.65; 7.65; 3.90	
U_3Si_2	*D5a*	7.33; 3.90	
U_3Si	*D0c*	6.02; 8.68	
$NpSi_2$	*Cc*	3.96; 13.67	
$PuSi_2$	*C32*	3.884; 4.082	99
VSi_2	*C40*	4.56; 6.36	
V_3Si	*A15*	4.71	
V_5Si_3	$D8_8$	7.12; 4.832	100
$NbSi_2$	*C40*	4.79; 6.58	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IVb: Si, Ge, Sn, Pb—*continued*			
Nb_5Si_3	$D8_8$	7.52; 5.238	100
$TaSi_2$	$C40$	4.77; 6.55	
$CrSi_2$	$C40$	4.42; 6.35	
CrSi	$B20$	4.62	
Cr_3Si	$A15$	4.56	
$MoSi_2$	$C11$	3.19; 7.83	101
Mo_3Si	$A15$	4.89	
Mo_5Si_3	$D8_8$	7.27; 4.992	100
WSi_2	$C11$	3.20; 7.81	101
Mn_4Si_7	tetr.	5.51; 17.42	
MnSi	$B20$	4.55	
Mn_5Si_3	$D8_8$	6.90; 4.80	
Mn_3Si	$A2$	2.85	
$ReSi_2$	$C11$	3.12; 7.66	
$FeSi_2$	tetr.	2.69; 5.13	
FeSi	$B20$	4.49	
Fe_5Si_3	$D8_8$	6.73; 4.70	
Fe_3Si	$D0_3$	5.64	
$CoSi_2$	$C1$	5.36	
CoSi	$B20$	4.44	
Co_2Si	$C37$	7.10; 4.91; 3.73	
$NiSi_2$	$C1$	5.40	
NiSi	$B20$	4.446	
NiSi	Bd	5.62; 5.18; 3.34	106
Ni_2Si (θ)	$B8$	3.81; 4.89 (>1 200°C)	106
(δ)	$C23$	7.03; 4.99; 3.72 (<1 200°C)	106
Ni_3Si (β_1)	$L1_2$	3.50 (<1 040°C)	
Ru_2Si_3	tetr.	5.52; 4.46	
RuSi (1)	$B2$	2.909	
(2)	$B20$	4.703	
$RuSi_{1.0-0.1}$	$B20$	4.703	297
RhSi	$B20$	4.672	107
Rh_2Si	$C23$	7.418; 5.279; 4.005	
Rh_5Si_3	orthorh.	10.07; 5.30; 3.88	293
Rh_3Si_2	$B8$	3.94; 5.047	
RhSi	$B31$	6.36; 5.53; 3.06	
PdSi	$B31$	6.12; 5.59; 3.37	
Pd_2Si	$C22$	6.48; 3.42	108
Os_2Si_3	tetr.	5.57; 4.47	
OsSi	$B2$	2.960	297
$IrSi_{0.3}$	BC tetr.		297
Ir_3Si	$D0_3$	5.22; 7.95	293
Ir_2Si	$C23$	7.615; 5.28; 3.98	
Ir_3Si_2	$B8_2$	3.96; 5.12	
$IrSi_3$	$D0_{18}$	4.31; 6.61	
PtSi	$B31$	5.92; 5.58; 3.60	
Pt_2Si	$L'2_b$	3.93; 5.91	109
Pt_2Si	$C22$	6.76; 3.45	110
BeZrSi	$B8_2$	3.71; 7.19	8
Pd_4Al_3Si	$B20$	4.830	83
$Cu_{15}Si_4$ (ε)	$D8_6$	9.69	
Cu_5Si	$A13$	6.21	
~Cu_7Si	$A3$	2.57; 4.18	
$Cu_{16}Mg_6Si_7$	$D8a$	11.67 ($A=116$)	111
Cu_3SiMg_2	$C14$	5.00; 7.87	
	$C36$	5.0; 16.0 (>870°C)	
AlNaSi	$C38$	4.13; 7.40	
$Al_{13}Cr_4Si_4$	cubic	10.917	112
$Al_9Mn_2Si_2$	cubic $Al_{19}Mn_{14}$	12.63	
Al_9Mn_3Si	$E9c$ $Al_{10}Mn_3$	7.51; 7.74	
AlFeSi (α)	hex.	12.3; 26.2	113
$Al_{21}Fe_3Si_5$	cubic	12.52	
Al_5FeSi	monocl.	6.11; 6.11; 41.4; 90° (pseudo-tetr.)	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IVb: Si, Ge, Sn, Pb–*continued*			
Al_3FeSi_2	tetr. Ga_5Pd	6.13; 9.46	
$AlNi_2Si$	*B*20	4.55	83
Al_8FeMg_3Si	*E*9*b*	6.62; 7.92	
$Al_5Cu_2Mg_8Si_6$	tetr.	10.30; 4.04	
Ge	*A*4	5.657 4	
Mg_2Ge	*C*1	6.37	
GaGe	*Bc*	4.001; 4.575; 10.845	114
$CaGe_2$	*C*12	10.49; 21° 42′	
Ca_2Ge	*C*23		102
Y_5Ge_3	$D8_8$	8.47; 6.35	298
$CeGe_2$	*Cc*	4.202; 14.153	299
$PrGe_2$	*Cc*	4.25; 13.94	
TiGe	*B*27	3.80; 5.22; 6.82	300
$TiGe_2$	*C*54	8.58; 5.02; 8.85	
Ti_5Ge_3	$D8_8$	7.54; 5.22	
$ZrGe_2$	*C*49	3.80; 1501; 3.76	
Zr_5Ge_3	$D8_8$	7.99; 5.59	115
Hf_5Ge_3	$D8_8$	7.88; 5.53	298
$\alpha ThGe_2$	*Cc*	4.106; 14.193	301
$ThGe_2$	*B*1	6.033	
Th_3Ge	*D*5*a*	7.971; 4.170	
$ThGe_3$	cubic	11.72	
V_3Ge	*A*15	4.76	
$NbGe_2$	*C*40	4.96; 6.77	
$TaGe_2$	*C*40	4.95; 6.74	
Ta_5Ge_3	$D8_8$	7.58; 5.23	115
Cr_3Ge	*A*15	4.645	337
CrGe	*B*20	4.78	
Cr_5Ge_3	*D*8*m*	9.41; 4.78	115
Mo_3Ge	*A*15	4.93	
Mn_5Ge_3	$D8_8$	5.053; 7.184	
$Mn_{3.25}Ge$	$D0_{19}$	5.35; 4.37 (at low temp.)	
	*A*3	(at high temp.)	
$FeGe_2$	*C*16	5.90; 4.94	
Fe_2Ge	*B*8	4.03; 5.02 ($Fe_{1.8}Ge$)	
CoGe	*D*7*a*	11.64; 3.80; 4.94 ($\beta = 101.10°$; $M = 8$)	293
Co_5Ge_8	*D*2*b*	7.64; 5.814 ($A = 26$)	
$CoGe_2$	*Ce*	5.65; 5.65; 10.8	
NiGe	*B*31	5.80; 5.37; 3.42	
Ni_2Ge	*B*8	3.95; 5.04 ($Ni_{1.8}Ge$)	
Ni_3Ge	$L1_2$	3.56	
GeRu	*B*20	4.546	302
Ge_3Ru_2	tetr.	5.709; 4 650	
PdGe	*B*31	6.25; 5.77; 3.47	
Pd_2Ge	*C*22	6.67; 3.52	108
$OsGe_2$	*Cg*	8.995; 3.094; 7.685 ($\beta = 110° 10'$; $M = 4$)	
Ir_4Ge_5	tetr.	5.62; 18.31	293
$IrGe_4$	hex.	6.211; 7.77	
Ir_3Ge_7	*D*8*f*	8.74	
IrGe	*B*31	6.27; 5.60; 3.48	
PtGe	*B*31	6.08; 5.72; 3.69	
Pt_2Ge	*C*22	6.67; 3.52	108
Pt_3Ge	*L*1, monocl.	7.931; 7.767; 7.767 ($\beta = 90.06$)	293
Pt_3Ge_2	*B*31	7.544; 3.423; 12.236	
Pt_7Ge_3	*B*31	3×5.48; 3.37; 6.22	
$PtGe_2$	*C*35	6.18; 5.76; 2.908	
PtGe	*A*1	3.91	
Cu_3Ge (1)	$D0_8$	4.16; 7.50 ($> \sim 600°C$)	
(2)	*D*0*a*	2.64; 5.45; 4.19 ($< \sim 600°C$)	
(3)	*A*2	(27–28 at. % Ge; between 620–700°C; superstructure with holes and $a' = 3a$). 4.168	
Cu_5Ge	*A*3	2.65; 4.28	
Co_4GaGe_3	*B*20	4.63	83

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IVb: Si, Ge, Sn, Pb–*continued*			
$Ni_{50}Ga_{42}Ge_8$	*B*20	4.64	83
Pd_5Al_4Ge	*B*20	4.86	83
Rh_5GaGe_4	*B*20	4.822	83
Sn grey	*A*4	6.489 2 (< 13.2°C)	
metallic	*A*5	5.831 8; 3.181 8 (> 13.2°C)	
$Na_{15}Sn_4$	~DS_6, orthorh.	9.79; 22.78; 5.65 (A = 30 to 40)	
Mg_2Sn	*C*1	6.75	
CaSn	B_c	4.349; 4.821; 11.52	114
$CaSn_3$	$L1_2$	4.73	
$LaSn_2$	$L1_2$	4.77	
$CeSn_3$	$L1_2$	4.71	
$PrSn_3$	$L1_2$	4.70	
Ti_5Sn_3	$D8_8$	8.05; 5.45	
Ti_3Sn	$D0_{19}$	5.92; 4.76	
Hf_5Sn_3	$D8_8$	8.39; 5.82	304
$ThSn_3$	$Z1_2$	4.718	292
USn_3	$L1_2$	4.62	
$MnSn_2$	*C*16	6.65; 5.43	
Mn_3Sn_2	*B*8	4.37; 5.48 (at low temp. superstructure)	
Mn_2Sn	*B*8	4.39; 5.46	
~$Mn_{11}Sn_3$	$D0_{19}$	5.67; 4.53 (< ~1 000 °C)	
$FeSn_2$	*C*16	6.52; 5.31	
FeSn	*B*35	5.29; 4.44	
Fe_3Sn_2	monocl.	13.53; 5.34; 9.20; 103° (M = 8)	
$Fe_{12}Sn_{10}$	$B8_2$	4.23; 5.21	
Fe_3Sn	$D0_{19}$	5.46; 4.36 (760–900 °C)	
$CoSn_2$	*C*16	6.35; 5.44	
CoSn	*B*35	5.27; 4.25	
Co_3Sn_2	*B*8	(high temp.) 4.12; 5.18	
Co_3Sn_2	$D5_{10}$	(< 550°C), 8.18; 7.08; 5.20	
Co_2MnSn	$D0_3$	5.991	116
Ni_3Sn_4	*D*7*a*	12.20; 4.06; 5.22; 105° 3′	
Ni_3Sn_2	*B*8	4.08; 5.18 (at low temp. superstructure	
	tetr.	9.20; 8.58 (A = 50) (> 900 °C)	
Ni_3Sn	*A*3	(> 900 °C)	
	$D0_{19}$	(< 900 °C), 5.28; 4.23	
Ni_4Sn	tetr. (?)	5.11; 4.88 (A = 10)	
Ni_2MgSn	$L2_1$	6.10	
Ni_2MnSn	$D0_3$	6.045	116
Ru_3Sn_7	*D*8*f*	9.35	
RhSn	*B*20	5.12	
~Rh_3Sn_2	*B*8	4.33; 5.54	
$RhSn_2$ (1)	*C*16	6.40; 5.64 (> 500°C)	
(2)	C_e	6.32; 11.97 (< 500°C)	117
	C_f	6.38; 17.88	118
$PdSn_4$	$D1_c$	6.38; 6.41; 11.47	
$PdSn_2$ (1)	C_e	6.48; 12.15	117
(2)	C_f	6.55; 24.57 (low temp. mod.)	118
	~*B*31 (monocl. deformed)	6.18; 3.93; 6.38; 88.5° (quenched from high temp.)	
PdSn	*B*31	6.13; 3.87; 6.32	
Pd_3Sn_2	*B*8	4.39; 5.70	
Pd_3Sn	$L1_2$	3.97	
Ir_3Sn_7	$D8_f$	9.36	
$IrSn_2$	*C*1	6.34	
IrSn	*B*8	3.99; 5.57	
$PtSn_4$	$D1_c$	6.38; 6.41; 11.33	
$PtSn_2$	*C*1	6.43	
Pt_2Sn_3	$D5_b$	4.33; 12.96	
PtSn	*B*8	4.10; 5.43	
Pt_3Sn	$D0_{19}$	4.00	
Cu_6Sn_5 (η)	*B*8	4.19; 5.09	119
~Cu_3Sn (ε)	*A*3	2.76; 4.32	119
	~*A*3 (orthorh. deformed)	5.51; 38.18; 4.32	120

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group IVb: Si, Ge, Sn, Pb–*continued*			
$\sim Cu_3Sn$ (ε')	$\sim A3$ (orthorh. deformed)	9.93; 5.50; 8.46	121
γCu_3Sn	orthorh.	4.772; 5.514; 4.335 (700 °C)	122
$\sim Cu_{10}Sn_3$	$\sim D8_5$	7.32; 7.85 D_3^1d; ($A=26$)	
$\sim Cu_{41}Sn_{11}$	$\sim D8_4$	17.92	
$Cu_{17}Sn_3$ (β)	$A2$	2.97 (stable >600°C)	
(β'')	orthorh.	4.55; 5.36; 4.31 ($A=8$; at low temp.)	
Cu_2MnSn	$L2_1$	6.15	
$(Cu, Ni)_3Sn$	$D0_3$	5.59	
Ag_3Sn	A_e	2.99; 5.14; 4.77	
$\sim Ag_5Sn$	$A3$	2.94; 4.77	
Ag_6Mg_3Sn	$L2_1$	6.60 [structural formula: $Ag_2Mg(Mg, Ag, Sn)$]	
$AuSn_4$	$D1c$	6.43; 6.47; 11.58	
$AuSn_2$	$C46$	6.845; 6.990; 11.760	80
AuSn	$B8$	4.31; 5.51	
Au_6Sn	$A3$	2.92; 4.77	
$ZnSn_2$	$C54$	9.55; 5.63; 9.90	123
CdSn (β)	hex.	3.226 3; 2.996 3	64
$CdSn_9$	hex.	3.21; 2.99	63
$\sim HgSn_{15}$ (1)	$A3$	3.20; 2.98 } orthorh. deformed on the Sn-poor end	
(2)	orthorh.	3.20; 5.55; 2.98 }	
$\sim InSn_7$	$A5$	3.181; 5.827	
$InSn_4$	hex.	3.21; 2.99	63
In_3Sn	$L1_2$ (deformed into tetr.)	4.94; 4.40	
Pb	$A1$	4.950 2	
LiPb	$B2$	3.52	
Li_3Pb	$D0_3$	6.687	124
Li_7Pb_2	hex.	4.751; 8.589	124
Li_8Pb_3	monocl. $C2/m$	8.240; 4.757; 11.03; $\beta=104°\ 25'$ ($M=2$)	125
$Li_{10}Pb3$	$D8_3$	10.08	
$Li_{22}Pb_5$	f.c.c.	20.8 ($M=16$)	305
Na_2Pb_5	$L1_2$	4.87	
NaPb	tetr.	10.580; 17.746	126
$Na_{15}Pb_4$	$D8_6$	13.29	
KPb_2	$C14$	6.66; 10.76	127
Mg_2Pb	$C1$	6.80	
$CaPb_3$	$L1_2$	4.89	
$SrPb_3$	$L1_2$ (deformed into tetr.)	4.96; 5.03	
$LaPb_3$	$L1_2$	4.89	
$CePb_3$	$L1_2$	4.86	
$PrPb_3$	$L1_2$	4.86	
Ti_4Pb	$D0_{19}$	5.962; 4.814	128
Zr_3Pb_3	$D8_8$	8.51; 5.85	123
UPb_3	$L1_2$	4.79 (because U and Pb scatter similarly no decision between $L1_2$ and $A1$-type was possible)	
$ThPb_3$	$L1_2$	4.856	292
$RhPb_2$	$C16$	6.65; 5.85	
$PdPb_2$	$C16$	6.84; 5.82	
PdPb	monocl.	7.08; 8.43; 5.56; 71°	
Pd_3Pb_2	$B8$	4.47; 5.71	
Pd_3Pb	$L1_2$	4.01	
IrPb	$B8$	3.99; 5.56	
$PtPb_4$	$D1_d$	6.65; 5.97	
PtPb	$B8$	4.25; 5.46	
Pt_3Pb	$L1_2$	4.05	
Ag_4Pb	$A3$	2.92; 4.76	129
$AuPb_2$	$C16$	7.31; 5.64	
Au_2Pb	$C15$	7.91	
$\sim In_3Pb$	$A6$	4.85; 4.50	
Tl_3Pb	$A1$	4.88 } strong indications that ordered structures $PbTl_3$ and	
Tl_7Pb	$A1$	4.86 } $PbTl_7$ exist	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group Vb: As, Sb, Bi			
As	*A*7	4.1359; $\alpha = 54° 7'$	
Li_3As	DO_{18}	4.39; 7.81	
LiAs	monocl.P^2_{1h}	5.79; 5.24; 10.70 ($\beta = 117.4°$; $M = 8$)	306
Na_3As	DO_{18}	5.09; 8.98	
K_3As	DO_{18}	5.78; 10.22	
Mg_3As_2	$D5_3$	12.33	
MgLiAs	*C*1	6.21	
LaAs	*B*1	6.13	
CeAs	*B*1	6.06	
PrAs	*B*1	6.00	
NdAs	*B*1	5.96	
ZrAs	*Bi*	3.80; 12.87	307
$ZrAs_2$	C_{23}	6.80; 9.02; 3.68	
TiAs	*B*8*i*	3.63; 6.14	130
	Bi	3.64; 12.3	130
CrAs	*B*31	6.21; 5.73; 3.48	
Cr_2As	*C*38	3.61; 6.33	
~MnAs (1)	*B*8	3.72; 5.70	131
(2)	*B*31		132
Mn_2As	*C*38	3.76; 6.27	
Mn_3As	*D*0*d*	3.78; 3.78; 16.26	
$FeAs_2$	*C*18	2.86; 5.20; 5.92	
FeAs	*B*31	6.02; 5.43; 3.37	
Fe_2As	*C*38	3.63; 5.97	
$CoAs_3$	DO_2	8.195	
$CoAs_2$	*C*18	—	
CoAs	*B*31	5.96; 5.15; 3.51	
$NiAs_3$	DO_2	8.26	
$NiAs_2$	*C*18	3.53; 4.78; 5.78 (Rammelsbergite)	
	*C*46	5.74; 5.81; 11.41 ($M \approx 8$) (para-Rammelsbergite)	
NiAs	*B*8	3.61; 5.03	
$Ni_{11}As_8$	tetr.	6.84; 21.83 ($M \approx 11$)	
Ni_5As_2	hex.	6.80; 12.48	
$PdAs_2$	*C*2	5.97	
$PtAs_2$	*C*2	5.96	
Cu_3As	cubic	9.59 ($M = 16$) (Domeykite)	
	DO_{21}	7.09; 7.23 (synthetic)	
Cu_3As	*A*3	2.58; 4.22 (part of Algodonite and Whitneyite)	
CuMgAs	*C*38	3.95; 6.23	
~Ag_8As	*A*3	2.89; 4.72	
AgMgAs	*C*1	6.24	
$ZnAs_2$	orthorh.	7.72; 7.99; 36.28 ($M = 32$)	133
Zn_3As_2	$D5_9$	11.78; 23.65	
ZnLiAs	*C*1	5.91	
ZnNaAs	*C*1	5.90	134
ZnCuAs	*C*1	5.87	
ZnAgAs	*C*1	5.90	134
Cd_3As_2	$D5_9$	8.95; 12.68	
AlAs	*B*3	5.62	
$AlLi_3As_2$	~*C*1	11.87; 11.98; 12.11 [orthorh. deformed (D^{27}_{2h}) superstructure]	
$GeAs_2$	orthorh. *Pbam*	14.76; 10.16; 3.728 ($M = 8$)	308
GaAs	*B*3	5.6534	309
InAs	*B*3	6.05084	309
SnAs	*B*1	5.72	
~Sn_3As_2	cubic, deformed	2.91; 88° 54' ($A = 1$)	
Sb	*A*7	4.54067; $\alpha = 57° 7'$	
Li_3Sb (α)	DO_{18}	4.70; 8.31	
(β)	DO_3	6.56	
NaSb	LiAs	6.80; 6.34; 12.48 ($\beta = 117.6°$)	306
Na_3Sb	DO_{18}	5.36; 9.50	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group Vb: As, Sb, Bi—*continued*			
K_3Sb	$D0_{18}$	6.03; 10.69	
Cs_3Sb	$B32$	9.147–9.188	135
Mg_3Sb_2	$D5_2$	4.57; 7.23	
MgLiSb	$C1$	6.61	
LsSb	$B1$	6.48	
CeSb	$B1$	6.40	
PrSb	$B1$	6.35	
NdSb	$B1$	6.31	
$TiSb_2$	$C16$	6.65; 5.80	
TiSb	$B8$	4.06; 6.29	
Ti_3Sb	$A15$	5.2186	310
	$D8m$	10.465; 5.2639 ($M=32$)	
Ti_3Sb	$D0_{19}$	5.95; 4.80	131
ThSb	$B1$	6.305	136
Th_3Sb_4	$D7_3$	9.353	136
$ThSb_2$	$C38$	4.344; 9.154	136
VSb_2	$C16$	6.54; 5.62	131
V_3Sb	$A15$	4.932 ($M=2$)	337
Nb_3Sb	$A15$	5.262 ($M=2$)	337
$CrSb_2$	$C18$	3.27; 6.02; 6.86	
CrSb	$B8$	4.11; 5.47	
MnSb	$B8$	4.12; 5.78	
Mn_2Sb	$C38$	4.078; 6.557	137
$FeSb_2$	$C18$	3.19; 5.82; 6.52	
FeSb to Fe_3Sb_2	$B8$	4.06–4.12; 5.13–5.17	
$CoSb_2$	$C18$	3.21; 5.78	
CoSb	$B8$	3.87; 5.18	
CoMnSb	$C1$	5.89	
$NiSb_2$	$C18$	3.21; 5.63; 6.23	
NiSb	$B8$	3.91; 5.13	
Ni_2Sb	tetr.	5.79; 6.00 ($A\approx15$) (Ni_3Sb_2?)	
Ni_3Sb	$D0a$	5.96	
NiMgSb	$C1$	6.04	
Ni_2MgSb	$L2_1$	6.05	
NiMnSb	$C1$	5.90	
Ni_2MnSb	$L2_1$	6.00	
RhSb	$B31$	6.32; 5.94; 3.87	
$PdSb_2$	$C2$	6.44	
PdSb	$B8$	4.07; 5.58	
Pd_5Sb_3	$B8$	4.44; 5.77	80
$IrSb_2$	$E1_b$	6.6; 6.5; 6.7; $B=115°$	13
$PtSb_2$	$C2$	6.43	
PtSb	$B8$	4.13; 5.47	
Cu_2Sb	orthorh.	2.78; 4.77; 4.38	80
Cu_2Sb (γ)	$C38$	3.97; 6.07	
Cu_2Sb_2 (β)	tetr. (?)	(>440 °C), 9.01; 8.57	
(β')	$D0_3$ (tetr. deformed) incompl. filled (*cf.* Cu_3Sb)	(<440 °C) (unstable)	
$Cu_{11}Sb_4$ to Cu_3Sb (θ)	$\sim A3$	(<400 °C), peritectic from β and γ (2×)2.45; (2×)4.34	
$\sim Cu_3Sb$	$D0_3$	(>400 °C) 6.00	
Cu_9Sb_2 (δ)	$\sim A3$	10.84; 8.61 ($A\simeq54$)	
$Cu_{11}Sb_2$ (η)	$\sim A3$ (orthorh.)	9.29; 8.18; 8.63	139
	$A3$	2.68; 4.32	140
CuMgSb	$C1$	6.15	
CuMnSb	$C1$	6.05	
$(Cu, Ni)_3Sb$	$D0_3$	5.86	
Ag_3Sb	$D0a$	4.847; 5.249; 5.993	
Ag_3Sb to Ag_7Sb	$\sim A3$	2.99–2.92; 4.84–4.80 (deformed similar phases)	
AgMgSb	$\sim C38$	—	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Group Vb: As, Sb, Bi—*continued*			
$AuSb_2$	*C*2	6.64	
ZnSb	*Be*	6.22; 7.74; 8.12	
$ZnMg_2Sb_2$	$D5_2$	4.37; 7.15	
CdSb	*Be*	6.47; 8.25; 8.53	
Cd_3Sb_2	monocl.	7.21; 13.51; 6.16; 100° 14′ ($M=4$)	
CdCuSb	*C*1	6.26	
AlSb	*B*3	6.135 5	309
GaSb	*B*3	6.095 4	309
InSb	*B*3	6.478 77	309
Tl_7Sb_2	$L2_2$	11.59	
SnSb	*B*1	5.88	
	*B*2	3.50	
$\sim AsSb_2$	cubic f.c.	11.06–11.12	
Bi	*A*7	4.746 0; $\alpha=57°\,14'$	
LiBi	$L1_0$	4.75; 4.25	
Li_3Bi	$D0_3$	6.71	
NaBi	$L1_0$	4.90; 4.80	
Na_3Bi	$D0_{18}$	5.45; 9.66	
KBi_2	*C*15	9.50	
K_3Bi	$D0_{18}$	6.18; 10.93	
Mg_3Bi_2	$D5_2$	4.67; 7.40	
MgLiBi	*C*1	6.75	
LaBi	*B*1	6.57	
CeBi	*B*1	6.49	
PrBi	*B*1	6.45	
Ti_2Bi_{17}	hex.	7.34; 10.73	220
$\sim Ti_4Bi$	$\sim D0_{19}$		
Ti_3Bi	tetr.	6.020; 8.204	312
$ZrBi_2$	*C*46	10.2; 15.5; 4.0 ($n=8$)	311
Th_3Bi_4	$D7_3$	9.559 ($M=4$)	141
$ThBi_2$	*C*38	4.492; 4.298; ($M=2$)	141
UBi	*B*1	6.36	
Ta_2Bi_{17}	hex.	7.39; 10.76	220
$MnBi_2$	tetr.	5.83; 5.35 ($M=2$)	
Mn_2Bi_3	orthorh.	4.31; 5.25; 6.31	
MnBi	*B*8	4.30; 6.12	
NiBi	*B*8	4.07; 5.35	
NiMgBi	*C*1	6.15	
$ReBi_{20}$	O_h^7	11.54	220
RhBi	*B*8	4.08; 5.66	
Pd_5Bi_3	*B*8	4.50; 5.80	80
$PtBi_2$	*C*2	6.68	
CuMgBi	*C*1	6.26	
Au_2Bi	*C*15	7.94	
InBi	*B*10	5.000; 4.773	142
In_2Bi	*C*32	5.50; 3.29 (disordered)	
$TiBi_2$	*C*32	5.65; 3.37 (disordered)	
Ti–Bi (?)	*C*32	5.64; 3.37	65
$\sim Tl_6Bi$	*A*1	4.85	
Pb_3Bi	*A*3	3.48; 5.78	
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S			
B (needles)	tetr.	10.14; 14.17	
(plates)	orthorh. (?)	17.86; 8.93; 10.13	144
(graphitic)	tetr.	8.57; 8.13	145
("more crystalline")	hex.	11.98; 9.54	
B	tetr.	8.75; 5.06	313
Be_2B	*C*1	4.663	314
BeB_3	hex.	9.79; 9.55	
BeB_6	tetr.	10.16; 14.28	
MgB_2	*C*32	3.084; 3.522	146

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Tc, Se, S—*continued*			
CaB_6	$D2_1$	4.15	
SrB_6	$D2_1$	4.19	
BaB_6	$D2_1$	4.28	
YB_6	$D2_1$	4.07	
LaB_6	$D2_1$	4.15	
LaB_{13}	f.c.c. O_h^6	10.44	220
EuB_6	$D2_1$	4.163	315
TbB_6	$D2_1$	4.11	316
TbB_4	*D1e*	7.13; 4.07	
CeB_6	$D2_1$	4.13	
CeB_4	*D1e*	7.21; 4.09	
PrB_6	$D2_1$	4.12	
NdB_6	$D2_1$	4.12	
GdB_6	$D2_1$	4.12	
ErB_6	$D2_1$	4.10	
YbB_6	$D2_1$	4.13	
Ti_2B_5	$D8_h$	2.98; 13.98	147
TiB_2	*C32*	3.03; 3.22	
TiB	*B27*	6.12; 3.06; 4.56	149
Ti_2B	*C32*	3.03; 3.23	(149, 150)
Ti_2B	tetr.	6.11; 4.56 ($M=4$; lattice primitive)	147
ZrB_{12}	*D2f*	7.41	151
ZrB_2	*C32*	3.17; 3.53	151
ZrB	*B1*	4.65	148 (149, 150)
ThB_6	$D2_1$	4.2	
ThB_4	*D1e*	7.26; 4.11	
UB_{12}	*D2f*	7.47	
UB_4	*D1e*	7.08; 3.98	
PuB	*B1*	4.92	317
PuB_2	*C32*	3.18; 3.94	
PuB_4	*D1e*	7.10; 4.014	
PuB_6	$D2_1$	4.115–4.140	
VB_2	*C32*	3.00; 3.06	
V_3B_4	$D7_b$	3.030; 13.18; 2.986	152
VB	B_f	3.10; 8.17; 2.98	
NbB_2	*C32*	3.09; 3.30	
Nb_3B_4	$D7_b$	3.31; 14.08; 3.14	
NbB	B_f	3.30; 8.72; 3.17	
Nb_9B	cubic	4.21 (> ~800°C)	
TaB_2	*C32*	3.08; 3.27	
Ta_3B_4	$D7_b$	3.29; 14.0; 3.13	
TaB	B_f	3.28; 0.867; 3.16	
Ta_2B	*C16*	5.78; 4.86	
CrB_2	*C32*	2.97; 3.07	
Cr_3B_4	*D7b*	2.98; 13.02; 2.95	
Cr_3B_4	$D7_b$	2.986; 13.02; 2.952	318
CrB	*Bf*	2.96; 7.81; 2.94	
Cr_5B_3	tetr.	5.46; 10.64	153
Cr_2B	*C16*	5.18; 4.31	153
Cr_4B	B_f	4.26; 7.38; 14.71	153
Mo_2B_5	*D8i*	3.01; 20.93	
MoB_2	*C32*	3.05; 3.11	
MoB	*Bg*	3.11; 16.97	
Mo_2B	*C16*	5.54; 4.74	
W_2B_5	*D8h*	2.98; 13.87	
WB_2	*C32*	3.02; 3.05	
WB (1)	B_f	3.19; 8.40; 3.07 (> 1 850°C)	
(2)	B_g	3.12; 16.93	
W_2B	*C16*	5.56; 4.74	
Mn_3B_4	$D7_b$	3.03; 12.86; 2.96	
MnB	*B27*	4.15; 5.56; 2.98	
Mn_2B	*C16*	5.15; 4.21	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
Mn_4B	$D1_f$	14.53; 7.29; 4.21	
ReB_2	hex.	2.900; 7.478 ($M=2$)	319
FeB	*B*27	4.05; 5.50; 2.95	
Fe_2B	*C*16	5.10; 4.24	
CoB	*B*27	3.95; 5.34; 3.04	
Co_2B	*C*16	5.01; 4.21	
Co_3B	$D0_{11}$	4.41; 5.23; 6.63	154
Ni_2B	*C*16	4.98; 4.24	
Ni_3B	$D0_{11}$	4.389; 5.211; 6 619	154
RuB	b.c.c.	7.02	320
RuB_2	orthorh.	2.865; 4.045; 4.645	
Rh_2B	orthorh.	5.42; 3.98; 7.44: ($M=4$)	155
Pd_3B_2	hex.	6.48; 3.42	
Pd_5B_2	monocl. *C*2/*a*	12.786; 4.955; 5.472 ($\beta=97°\,2'$; $M=4$)	321
Pd_3B	$D0_{11}$	5.463; 7.567; 4.852	
OsB	B_h	2.871; 2.876	
OsB	cubic	7.03	
Pt_3B		2.77; 2.95	
AlB_2	*C*32	3.00; 3.25	
AlB_{10}	orthorh.	8.881; 9.100; 5.690 ($M=2$)	339
AlB_{12} (Mod. I)	monocl. f.c.	8.51; 10.98; 9.40; 110° 54' ($M=8$)	
(Mod. II)	tetr.	10.28; 14.30 ($A=196$)	
$Al_6Mo_7B_7$	—	—	
B_3Si	hex. *R*3*m*	6.319; 12.713	322
C	*A*4	3.560 9 (diamond)	
	*A*9	2.461 2; 6.709	
KC_8	~*A*9	4.97; 21.35	
KC_{16}	~*A*9	4.94; 17.45	
RbC_8	hex.	4.926; 22.78	
RbC_{16}	hex.	4.95; 17.99	
CsC_8	hex.	4.945; 17.76	
CsC_{16}			
Be_2C	*C*1	4.33	
MgC_2	tetr.	5.55; 5.03 ($M=4$; similar to ThC_2?)	
Mg_2C_3	hex.	7.45; 10.61 ($M=8$)	
CaC_2	*C*11	5.48; 6.37	
SrC_2	*C*11	5.81; 6.68	
BaC_2	*C*11	6.22; 7.06	
LaC_2	*C*11	3.94; 6.572	323
La_2C_3	b.c.c.	8.803–8.819	
CeC_2	*C*11	5.48; 6.48	
PrC_2	*C*11	5.44; 6.38	
NdC_2	*C*11	5.41; 6.23	
TiC	*B*1	4.32 ($TiC_{0.3}$ has $\alpha=4.26$)	
ZrC	*B*1	4.67	
HfC	*B*1	4.46	
ThC_2	*C*11	5.85; 5.28	156
	Cg	6.53; 4.24; 6.56; 104°	157
ThC	*B*1	5.34 (complete solid solution with ThC_2 at ~2 300 °C Wilhelm[158])	
$\sim UC_{2.3}$	*C*11	3.51; 5.97	159
$UC_{0.4}$	*C*11	3.54; 5.97	160
UC_2	*C*11	3.55; 6.00	161
U_2C_3	*D*5*c*	8.09	162
UC	*B*1	4.95	
Pu_2C_3	*D*5*c*	7.13	
PuC	*B*1	4.91	
VC	*B*1	4.17	
$\sim V_6C$	*L*'3	2.86; 4.54	
NbC	*B*1	4.424–4.457	163
NbC (α)	*A*2	3.301 2	324
(β)	hex.	3.120–2.138; 4.957–4.974	
(δ)	*B*1	4.430 9–4.469 0	
Nb_2C	hex.	3.12; 4.95	163

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
Nb_3C to			
Nb_4C	*L'*1	~4.40, depending on composition	
TaC	*B*1	4.45	
Ta_2C	*L'*3	3.09; 4.93	
Ta to $TaC_{0.03}$	*A*2	3.306	164
$\beta TaC_{0.38}$ to			
$TaC_{0.5}$	*C*6	3.101; 4.937	164
$\gamma TaC_{0.38}$ to			
$TaC_{0.5}$	*B*1	4.420	164
$\delta TaC_{0.38}$ to			
$TaC_{0.5}$	hex.	2.46; 6.69	164
Cr_7C_3	$D10_1$	4.526; 7.01; 12.14	
Cr_7C_3	hex.	13.98; 4.52 ($A \approx 80$) (isom. with Mn_7C_3)	
Cr_3C_2	$D5_{10}$	11.46; 5.52; 2.82	
$Cr_{23}C_6$	$D8_4$	10.64	
MoC (γ)	B_k	2.90; 2.81	
(γ')	B_l	2.93; 10.97	
MoC_{1-x}	*B*1	4.27 (perhaps only as substructure)	
Mo_2C	*L'*3	3.01; 4.74	
WC	*Bh*	2.90; 2.83	
W_2C	*L'*3	2.99; 4.71	
$W_2Cr_{21}C_6$	$D8_4$ ordered	—	
Mn_7C_3	hex.	13.87; 4.53 ($A \approx \leqslant \approx$) (isom. with Cr_7C_3)	
$Mn_{23}C_6$	$D8_4$	10.59	
$Fe_{20}C_9$	orthorh.	9.06; 15.69; 7.93 ($M=4$); or hex. with $a'=2a$, $c'=c$, $M'=8$	165
Fe_2C	hex	2.76; 4.35	166
Fe_3C	$D0_{11}$	4.52; 5.09; 6.75 (Cementite)	
('ε')	hex.		167
εFeC	hex.	4.767; 4.354	325
Fe (+0.25% C)	*L*2 (deformed tetr.)	2.842; 3.008 } Martensite at low temp.	
(+0.75% C)	*L*2 (deformed tetr.)	2.850; 2.939 }	
Fe (+C)	*A*1	3.6 (Austenite at high temp.)	
$\sim Fe_6Al_2C$	$L1_2$	3.72–3.78	
Fe_3Mo_3C	$E9_3$	11.1	
$Fe_{21}Mo_2C_6$	$D8_4$ ordered	10.63	
Fe_3W_3C	$E9_3$	11.087	
$Fe_{21}W_2C_6$	$D8_4$ ordered	10.54	
$Fe_3W_{10}C_4$	hex.	~7.85; ~7.85 (isom. Co, Ni-compounds)	
$Fe_3W_6C_2$	cubic	~11.25 (isom. Co, Ni-compounds)	
$\sim(Cr,Fe)_2C$	cubic f.c.	3.62 > 1 000°C (below 1 000°C Cr_7C_3-type)	
Co_2C	*C*18	2.910; 4.469; 4.426	326
Co_3C	$D0_{11}$	4.483; 5.033; 6.731	
Co_3W_3C	$E9_3$	11.01	
$Co_3W_9C_4$	hex.	7.286; 7.286	168
$Co_3W_{10}C_4$	hex.	7.85; 7.85 (isom. Fe, Ni-compounds)	
$Co_2W_6C_2$	$E9_3$	11.25	
Ni_3C	hex.	2.628; 4.306	169
Ni_3W_3 (θ)	$E9_3$	11.217	170
Ni_3W_6C (η)	$E9_3$	10.873	170
$Ni_3W_6C_2$	cubic f.c.	~11.25	
$Ni_3W_{10}C_4$	hex.	~7.85; ~7.85	
$Ni_3W_{16}C_6$	hex.	7.818 3; 7.818 0	170
Al_4C_3	$D7_1$	3.33; 24.94	
$AlMn_3C$	$L1_2$	3.83	
$\sim AlFe_3C$	$L1_2$	3.72–3.78	
SiC	*B*3	4.35 } there are several other modifications described	
	*B*5	3.08; 10.08 } with the *B*5-type	
B_4C	$D1g$	5.60; 12.12	
$B_{44}Al_3C_2$	D^{12}_{4h}	12.55; 10.18 ($M=4.31$) (diamond-type boron)	
	monocl.	17.64; 25.0; 10.26; ≈90° (?) (graphite-type boron)	
P (red)	cubic	11.31 ($A=66$)	
(white)	*I*432	18.51 ($A=224$; other possible space groups: Im3m and I43m)	
Li_3P	$D0_{18}$	4.26; 7.58	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
Na_3P	$D0_{18}$	4.98; 8.80	
Be_3P_2	$D5_3$	10.15	
Mg_3P_2	$D5_3$	12.01	
MgLiP	$C1$	6.023	
AlP	B_3	5.42	
GaP	B_2	5.4505	309
InP	B_3	5.868 75	309
LaP	$B1$	6.01	
CeP	$B1$	5.90	
PrP	$B1$	5.86	
NdP	$B1$	5.83	
Th_3P_4	$D7_3$	8.60	
Th_4P_3	$B1$	5.82	
U_3P_4	$D7_3$	8.20	
UP	$B1$	5.59	
Np_3P_4	$D7_3$	—	
V_3P	S_4^2	(similar to Cr_3P)	
CrP	$B31$	5.93; 5.36; 3.12	
Cr_3P	S_4^2	9.13; 4.56 [isom. with (V, Mn, Ni, Fe)$_3$P]	
WP	$B8$ (orthorh. deformed)	(?)	
MnP	$B31$	5.91; 5.25; 3.17	
Mn_2P	$C22$	6.07; 3.45	
Mn_3P	$D0_e$	9.16; 4.59 (isom. Cr_3P)	
FeP_2	$C18$	2.73; 4.98; 5.66	
FeP	$B31$	5.78; 5.18; 3.09	
Fe_2P	$C22$	5.93; 3.45	
Fe_3P	$D0_e$	9.10; 4.45 (isom. Cr_3P)	
CoP	$B31$	5.59; 5.07; 3.27	
Co_2P	$C23$	6.66; 5.71; 3.53	
Ni_2P	$C22$	5.85; 3.37	
Ni_7P_3	cubic b.c. (?)	8.63 ($M=6$)	
Ni_3P	$D0_e$	8.92; 4.39 (isom. Cr_3P)	
Rh_3P	$C1$	5.51	
Ir_2P	$C1$	5.54	
PtP_2	$C2$	5.68	
Cu_3P	$D0_{21}$	6.94; 7.14	
ZnP_2	tetr.	5.07; 18.65 (isom. with CdP_2)	
Zn_3P_2	$D5_9$	8.10; 11.45	
ZnLiP	$C1$	5.77	
CdP_2	tetr.	5.28; 19.70 (isom. with ZnP_2)	
Cd_3P_2	$D5_9$	8.75; 12.28	
AlP	$B3$	5.42	
$AlLi_3P_2$	orthorh.	11.47; 11.61; 11.73 (orthorh. deformed, with superstructure)	
GaP	$B3$	5.44	
InP	$B3$	5.86	
Li_3N	$C32$	3.66; 3.88	
Be_3N_2	$D5_3$	8.13	
Mg_3N_2	$D5_3$	9.95	
MgLiN	$C1$	4.97	
Ca_3N_2 (α)	$D5_3$	11.40 (high temp. mod.)	
(β)	pseudo-hex.	3.55; 4.11 at 300°C (low temp. mod.)	
ScN	$B1$	4.44	
LaN	$B1$	5.28	
CeN	$B1$	5.01	
PrN	$B1$	5.16	
NdN	$B1$	5.14	
EuN	$B1$	5.007	172
GdN	$B1$	4.99	
SmN	$B1$	5.048 1	172
YbN	$B1$	4.785 2	172
TiN	$B1$	4.24	
$TiLi_3N_3$	$E9_d$	9.73	173

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
ZrN	*B*	4.63	
Th_2N_3	$D5_2$	3.88; 6.18	
UN_2	*C*1	5.32	
U_2N_3	$D5_3$	10.70	
UN	*B*1	4.89	
NpN	*B*1	4.89	
PuN	*B*1	4.90	
~VN	*B*1	4.13	
$VN_{0.71}$	*B*1	4.07	
$VN_{0.4}$	*L*'3	2.84; 4.55 [superstructure $a' = a\sqrt{3}$; similar to $(Fe, Ni, Co)_2N$] $Co\}_2N$	
NbN (1)	*B*1	4.38	
(2)	$B8_1$	2.93; 5.45	
(3)	B_t	2.95; 11.25	
$\sim NbN_{0.75}$	B_g	4.38; 8.68	
$\sim Nb_2N$	*L*'3	3.05; 4.96	
TaN	hex.	5.181; 2.902	174
Ta_2N	*L*'3	3.06; 4.96	
CrN	*B*1	4.14	
Cr_2N	*L*'3	2.76; 4.46	
MoN	*Bh*	2.86; 2.80	
Mo_2N (β)	*L*'6	4.18; 4.02	
(γ)	*L*'1	4.17	
W_2N (β)	*L*'1	4.12	
(γ)	*B*1	4.12 (4 W in simple cubic cell; perhaps $a' = 4 \times 4.12$)	
Mn_3N_2	*L*'6	4.19; 4.03	
Mn_4N	*L*'1	3.85	
$ReN_{0.4}$	*L*'1	3.92	
Fe_2N (ξ)	orthorh.	5.52; 4.83; 4.43 (deformed *A*3-type with superstructure; detailed description *see* Jack[167, 171])	
Fe_2N (ε)	*hex. L*'3	2.76; 4.43 } complex superstructures; *see* Jack[171]	
Fe_3N (ε)	hex.	2.72; 4.39 }	
Fe_4N (ε)	hex.	2.66; 4.34 }	
Fe_4N (γ')	*L*'1	3.80	
Fe_8N (α'')	*D2g*	5.72; 6.29	
Co_2N	*L*'3 (orthorh. deformed) *C*18	2.84; 4.63; 4.33	
Co_3N	~*L*'3	2.66; 4.35 ($a^* = 2a$)	
$CoLi_2N$	~*C*32	3.74; 3.62	
Ni_3N	~*L*'3	2.67; 4.31 (isom. ε-Fe_3N)	
$\sim NiLi_2N$	~*C*32	3.77; 3.52	
Cu_3N	$D0_9$	3.81	
$\sim CuLi_2N$	~*C*32	3.68; 3.77	
Zn_3N_2	$D5_3$	9.74	
ZnLiN	*C*1	4.89 (ordered)	
Cd_3N_2	$D5_3$	10.79	
AlN	*B*4	3.10; 4.97	
$AiLi_3N_2$	*E9d*	9.48	
GaN	*B*4	3.18; 5.17	
$GaLi_3N_2$	*E9d*	9.61	
InN	*B*4	3.53; 5.69	
α Si_3N_4	hex. D_6^2-P31c	7.758; 5.623	327
β Si_3N_4	hex. C_{6h}^2-P6/3*m*	7.603; 2.909	
Si_2ON	orthorh.	5.498; 8.877; 4.853	
Si_xN	hex.	4.534; 4.556	
Si_3N_4	orthorh.	13.38; 8.60; 7.74	
$SiLi_3N_3$	*E9d*	9.43	173
Ge_3N_4	orthorh.	13.84; 9.06; 8.18	
$GeLi_3N_3$	*E9d*	9.66	173
BN	*Bk*	2.50; 6.66	
Al_5C_3N	$E9_4$	3.28; 21.55	
Po (α)	*Ah*	3.35	
(β)	*Ai*	3.37; 98° 13'	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
PbPo	*B*1	—	
Te	*A*8	4.456 6; 5.926 4	175
Li_2Te	*C*1	6.50	
Na_2Te	*C*1	7.32	
K_2Te	*C*1	8.15	
$K_{2.67}$(Sb, Te)	~*C*1	8.40 } a continuous series of unit crystals between K_2Te and	
$K_{2.4}$(Te, Sb)	~*C*1	8.32 } K_3Sb appears probable at high temp.	
$K_{2.25}$(Te, Sb)	~*C*1	8.2 }	
BeTe	*B*3	5.61	
MgTe	*B*4	4.53; 7.38	
CaTe	*B*1	6.34	
SrTe	*B*1	6.65	
BaTe	*B*1	6.99	
EuTe	*B*1	6.57	
YbTe	*B*1	6.34	
$TiTe_2$	*C*6	3.77; 6.54	
TiTe	*B*8	3.83; 6.39	
Ti_3Te_4	tetr. $14/mc_45$	10.164; 3.772 0	328
UTe	*B*1	6.151	176
U_3Te_4	$D7_3$	9.378	176
UTe_2	*C*38	4.243; 8.946	
VTe	*B*8	3.81; 6.12	
~CrTe	*B*8	3.89–3.98; 5.91–6.21	
$MoTe_2$	*C*7	3.519; 13.964	329
WTe_2	orthorh.	3.490; 6.282; 14.073	177
$MnTe_2$	*C*2	6.94	
MnTe	*B*8	4.12; 6.70	
$FeTe_2$	*C*18	3.85; 5.34; 6.26	
FeTe	*B*8	3.80; 5.65	
$CoTe_2$	*C*6	3.78; 5.40	
	*C*18	3.88; 5.30; 6.30	
CoTe	*B*8	3.88; 5.37	
$NiTe_2$	*C*6	3.86; 5.30	
NiTe	*B*8	3.96; 5.35	
$RuTe_2$	*C*2	6.36	
$PdTe_2$	*C*6	4.03; 5.12	
PdTe	*B*8	4.13; 5.66	
$OsTe_2$	*C*2	6.37	
$PtTe_2$	*C*6	4.01; 5.20	
Cu_2Te	*Ch*	4.24; 7.27	
Cu_2Te	cubic f.c.	6.10 ($A=12$)	80
CuTe	orthorh.	3.10; 4.02; 6.86	80
$Cu_{2-x}Te$	~*C*38	3.98; 6.12	
Ag_2Te	~*C*1	(>150°C) 6.57 (high temp. mod.)	
	orthorh.	13.0; 12.7; 12.2 (low temp. mod.)	
	monocl.	5.98; 6.31; 5.56; 75° 24′ (Hessite)	
(Au, Ag)Te_2	*C*34	7.18; 4.40; 5.07; ~90° (Calaverite)	
	*C*46	16.51; 8.80; 4.45 (Krennerite)	
$AuAgTe_2$	*E*1*b*	8.94; 4.48; 14.59; 145° 24′	
ZnTe	*B*3	6.09	
CdTe	*B*3	6.46	
HgTe	*B*3	6.429 (Coloradoite)	175
Ga_2Te_3	~*B*3	5.89	
Te_3Al_2	*B*4	4.07; 6.93	330
InTe	*B*37	8.42; 7.12	63,80
In_2Te_3	~*B*3	6.16	
TeTl	b.c.tetr.	12.950; 6.175	331
Te_3Tl_2	monocl.	13.5; 6.5; 7.9 ($\beta=73°$)	
γ-Te_3Tl_2	b.c. tetr.	8.92; 12.63	
SnTe	*B*1	6.28	
PbTe	*B*1	6.44 (Altaite)	
As_2Te_3	monocl.	14.4; 4.05; 9.92: $B=97°$	178
Sb_2Te_3	hex	4.24; 29.90	179
Te_2SbTl	$F5_1$	8.177 ($\alpha=31°\,24'$)	332

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Sc, S—*continued*			
Te_2BiTl	$F5_1$	8.137 ($\alpha = 32° 18'$)	
Bi_2Te_3	$C33$	10.45; 24° 8′ (Tellurobismuthite)	
Se (γ)	$A8$	4.365 9; 4.953 7	
(α)	Ak	9.05; 9.07; 11.61; 90° 46′	
(β)	$A1$	12.85; 8.07; 9.31; 93° 8′	
Li_2Se	$C1$	6.01	
Na_2Se	$C1$	6.80	
K_2Se	$C1$	7.68	
BeSe	$B3$	5.13	
MgSe	$B1$	5.45	
CaSe	$B1$	5.91	
SrSe	$B1$	6.23	
BaSe	$B1$	6.59	
Y_5Se_3	$D8^8$	8.40; 6.30	333
EuSe	$B1$	6.17	
YbSe	$B1$	5.87	
$TiSe_2$	$C6$	3.54; 5.99	
TiSe	$B8$	3.56; 6.22	
$ZrSe_3$	monocl.	5.41; 3.77; 9.45 ($\beta = 97.5°$)	340
$ZrSe_2$	$C6$	3.79; 6.18	
U_3Se_4	$D7_3$	8.804	334
U_2Se_3	$D5_8$	11.33; 10.941; 4.06	334
$ThSe_2$	$C23$	4.98; 7.50; 9.38	
Th_7Se_{12}	$D8k$	11.56; 4.35	
Th_2Se_3	$D5_8$	11.32; 11.55; 4.26	
ThSe	$B1$	5.86	
USe_3	monocl.	5.68; 4.06; 19.26: ($d = 7.25$)	180
$VSe_{1.6}$ to VSe_2	$C6$	3.35; 6.12	
VSe	$B8$	3.58; 5.98	
Cr_2Se_3	$B8$	3.60; 5.77	
CrSe	~$B8$ (monocl.)	55–58 at. % Se: 6.30; 3.60; 5.85; 90° 30′	
	$B8$	50–54 at. % Se: 3.68; 6.02	
$CrNaSe_2$	$F5_1$	3.71; 20.29	
$CrK_{0.5}Se_2$	~$F5_1$	3.44; 24.2	
$CrRbSe_2$	$F5_1$	3.43; 26.9	
WSe_2	$C7$	3.29; 12.97	
$MnSe_2$	$C2$	6.42	
MnSe (α)	$B1$	5.45	
(β)	$B3$	5.82	
(γ)	$B4$	4.12; 6.72	
$FeSe_2$	$C18$	3.58; 4.79; 5.72	
FeSe	$B8$ to $B8$ monocl.	3.64; 5.96 } 50–56 at. % Se	
	deformed	6.25; 3.58; 5.81; 91° }	
	$B10$	44 at. % Se: 3.77; 5.52	
$CoSe_2$	$C2$	5.85	
CoSe	$B8$	3.61; 5.28	
$NiSe_2$	$C2$	6.02	
NiSe	$B8$	3.66; 5.33	
	$B13$	9.84; 3.18	
$RuSe_2$	$C2$	5.92	
$RhSe_2$	$C2$	6.015 (63.6%): 5.985 (71.4%)	181
$OsSe_2$	$C2$	5.93	
$PtSe_2$	$C6$	3.72; 5.06	
CuSe	~$B18$	3.94; 17.25 (superstructure $a' = 12a$) (Klockmannite)	
Cu_2Se	~$C1$	5.84 (Berzelianite)	
Ag_2Se	~$C1$	(> 133 °C), 4.98 (at 170 °C) (Naumannite)	
ZnSe	$B3$	5.66	
$ZnCr_2Se$	$H1_1$	10.44 ('normal' $H1_1$-type)	182
CdSe	$B3$	6.04	
	$B4$	4.30; 7.01	
$CdCr_2Se_4$	$H1_1$	10.72 ('normal' $H1_1$-type)	182
HgSe	$B3$	6.074 (Tiemannite)	175

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
GaSe	hex.	3.73; 15.89	63, 184, 185
	hex.	3.74; 23.86	63,
Ga_2Se_3	~*B*3	5.43	184
In_2Se_3	h.c.p. (room temp.)	4.01; 19.24	186
TlSe	*B*37	8.02; 7.00	
$GeSe_2$	orthorh.	7.003; 12.221; 23.04	
GeSe	*B*16	4.38; 3.83; 10.79 ($M=4$)	336
SnSe	*B*16	4.46; 4.19; 11.57	187
PbSe	*B*1	6.14; (Clausthalite)	
Sb_2Se_3	$D5_8$	11.58; 11.68; 3.98	
Bi_2Se_3	*C*33	4.14; 28.59 ($A=15$)	80
S (orthorh.)	*A*16	10.464; 12.866; 24.486	
(monocl.)	C_2^5h	10.9; 10.9; 11.0; 83° 16′ ($A=48$)	
(rhomb.)	*C*19	10.9; 4.26 ($A=18$)	
(fibre)	monocl.	26.4; 9.3; 12.3; 79° 15′ ($C=9.3$ = fibre axis; $A=112$)	
Li_2S	*C*1	5.71	
Na_2S	*C*1	6.53	
K_2S	*C*1	7.39	
Rb_2S	*C*1	7.65	
BeS	*B*3	4.86	
MgS	*B*1	5.19	
CaS	*B*1	5.69 (Oldhamite)	
SrS	*B*1	6.01	
BaS	*B*1	6.37	
La_2S_3	$D7_3$	8.71	
Ce_2S_3	$D7_3$	8.617	
Ce_3S_4	$D7_3$	8.608	
CeS	*B*1	5.77	
DyS	*B*1	5.96	
Ac_2S_3	$D7_3$	8.97	
TiS_2	*C*6	3.40; 5.69	
ThS_2	*C*23	4.26; 7.25; 8.60	
Th_7S_{12}	*D*8*k*	11.04; 3.98	
Th_2S_3	$D5_8$	10.97; 10.83; 3.95	
ThS	*B*1	5.67	
ZrS_2	*C*6	3.68; 5.85	
U_2S_3	$D5_8$	10.39; 10.63; 3.88	
US	*B*1	5.47	
Np_2S_3	$D5_8$	10.3; 10.6; 3.85	
Pu_2S_3	$D7_3$	8.44	
PuS	*B*1	5.53	
Am_2S_3	$D7_3$	8.43	
Vs to $V_{0.84}S$	*B*8	3.36; 5.81	
TaS_2	*C*6	3.40; 5.90	
CrS	~*B*8	50.0–52.4 at. % S: 12.00; 11.52	
CrS	*B*8	52.4–54.2 at. % S; 3.45; 5.75	
	*B*8 with monocl. deformed	55–59 at. % S: 5.95; 3.42; 5.63; 91° 44′	
	*B*8 with ordered vacant sites	~60 at. % S	
$CrNaS_2$	$F5_1$	3.51; 19.57	
$CrKS_2$	$F5_1$	3.62; 21.16	
$CrRbS_2$	$F5_1$	3.59; 16.20 or 5.74; 34° 21′	
MoS_2	*C*7	3.15; 12.30 (Molybdenite)	
WS_2	*C*7	3.15; 12.3 (Tungstenite)	
MnS_2	*C*2	6.10	
MnS	*B*1	5.21 (Alabandite)	
	*B*3	5.60	
	*B*4	3.98; 6.43	
$MnCr_2S_4$	$H1_1$	10.06	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
FeS_2	*C*2	5.40 (Pyrites)	
	*C*18	4.44; 5.41; 3.83 (Marcasite)	
~FeS	*B*8	3.447; 5.761	183, 189
Room temp. modifications:			
(α')	*B*8	50.0–51.0 at. % S: 5.96–5.97; 11.74–11.58	
(α'')	*B*8	51.0–52.3 at. % S: 3.44; 5.79–5.74	
(β)	*B*8	52.3–53.5 at. % S: 3.44–3.43; 5.74–5.69	
High temp. modifications:			
(β)	*B*8	~100°C to ~320°C, 50.0–~54.0 at. % S	
(δ)	*B*8	> ~320°C, lattice parameters different from β-modification (~0.5%) with different temp. coeff.	
FeS	*B*9	3.444; 5.876	
$Fe_{1.78}S_2$	*B*8 (monocl. deformed)	5.94; 3.43; 5.69; 89° 38′ (natural material)	190
$Fe_{2-x}S_2$	~*B*8	3.44; 5.82 (superstructure with $a' = 3 \times 3.44$ and $c' = 2 \times 5.82$; Graham[191])	
Fe_7S_8	~*B*8	6.86; 11.9; 22.7; 89° 33′ (detailed superstructure proposed by Bertant192)	
$FeKS_2$	*F*5*a*	7.05; 11.28; 5.40; 112° 30′	
$FeCr_2S_4$	$H1_1$	9.989 (ordered version of $D7_2$)	193
	$D7_2$	9.97	194
CoS_2	*C*2	5.52	
Co_3S_4	$D7_2$	9.38 (Linnaeite)	
CoS	*B*8	51–53 at. % S: 3.37–3.36; 5.18–5.16 (Jaipurite)	
Co_9S_8	$D8_9$	9.91	
$CoCr_2S_4$	$H1_1$	9.91	
NiS_2	*C*2	5.68	
Ni_2S_3	monocl.	$b = 3.2$ (Parkerite)	
Ni_3S_4	$D7_2$	9.46	
NiS	*B*8	3.43; 5.33 (high temp. mod.)	
NiS	*B*13	9.59; 3.15 (low temp. mod.)(Millerite)	
Ni_6S_5	D_{2h}^{17} orthorh.	11.22; 16.56; 3.27 ($M = 4$)	
Ni_3S_2	*D*5*e*	4.04; 90° 18′	
$(Ni, Fe)_9S_8$	$D8_9$	10.1 (Pentlandite)	
Ni_2FeS_4	$D7_2$	9.45	
RuS_2	*C*2	5.59	
RhS_2	*C*2	5.57	
PdS	*B*34	6.43; 6.63	
OsS_2	*C*2	5.64	
PtS_2	*C*6	3.54; 5.02	
PtS	*B*17	4.91; 6.10 (Cooperite)	
(Pt, Pd, Ni)S	*B*34	6.37; 6.58 (Braggite)	
CuS	*B*18	3.75; 16.2 (Covellite)	
$Cu_{1.8}S$	$C1_b$	5.56	
Cu_2S (γ)	orthorh.	11.90; 27.28; 13.41 (C_{2v}^{15} AbZm; S ≈ hex. cl. packed; 105°C)	
(β)	$D6_h^4$	3.89; 6.68 ($M = 2$; structures proposed by Belov[195] and Ueda[196] differ *cf.*[197])	
Cu_3VS_4	$H2_4$	5.38 (Sulvanite)	
$CuFeS_2$	$E1_1$	5.24; 10.30 (Chalcopyrite)	
$CuFe_2S_3$	*E*9*e*	6.23; 11.12; 6.46 (Cubanite)	
Cu_5FeS_4	~*B*3	$2 \times 5.49 > 220$ °C	
	orthorh.	21.94; 21.94; 10.97 ($M = 32$; superstructure of orthorh. deformed *B*3-type)(Bornite)	
$CuCo_2S_4$	$H1_1$	9.46 (Carrollite)	
Ag_2S	$C1_b$	4.88 (> 180°C) (Acanthite)	
	monocl.	(< 180°C)	
$AgFeS_2$	$E1_1$	5.66; 10.30	
ZnS	*B*3	5.40 (Zincblende)(low temp. mod.)	
	*B*4	3.811; 6.23 (Würtzite)(high temp. mod.)	
	*B*5	3.806; 12.44	
	cf. SiC	3.813; 18.69	
	cf. SiC	3.822; 46.79	
$ZnAl_2S_4$	$H1_1$	9.97 (< ~1 000°C)	
	*B*4	3.76; 6.13 > ~1 000°C	

Table 6.1 STRUCTURES OF METALS, METALLOIDS AND THEIR COMPOUNDS—*continued*

Element or compound	*Structure type*	*Lattice constants, remarks*	*Refs.*
Metalloids, *etc.*: B, C, P, N, Po, Te, Se, S—*continued*			
$ZnCr_2S_4$	$H1_1$	9.9	
CdS	*B*4	4.13; 6.69 (Greenockite)	
	*B*3	5.81	
$CdMg_2S_4$	$H1_1$	10.80	
$CdCr_2S_4$	$H1_1$	10.19	
HgS	*B*3	5.84 (Metacinnabarite)	
	*B*9	4.14; 9.49 (Cinnabar)	
$HgCr_2S_4$	$H1_1$	10.21	
Al_2S_3	*B*4	3.579; 5.829	
Ga_2S_3 (α)	*B*3	5.18 < 550°C	
(β)	*B*4	3.69; 6.03 > 550°C	
InS	*B*16	3.93; 4.43; 10.62: ($A = 8$)	198
In_2S_3 (α)	*B*1	5.37 <300°C	
(β)	$H1_1$	10.74 >300°C	
In_2BeS_4	$H1_1$	10.77	
In_2CaS_4	$H1_1$	10.77	
In_2MgS_4	$H1_1$	10.69	
In_2MnS_4	$H1_1$	10.69	
In_2FeS_4	$H1_1$	10.60	
In_2CoS_4	$H1_1$	10.56	
In_2NiS_4	$H1_1$	10.46	
In_2HgS_4	$H1_1$	10.81	
TlS	*B*37	7.79; 6.80	
Tl_2S	*C*6	12.20; 18.17	
SiS_2	*C*42	5.60; 5.53; 9.55	
GeS_2	*C*44	11.66; 22.34; 6.86	
GeS	*B*16	4.29; 10.42; 3.64	
(Fe, Ge)Cu_3S_4	*B*3	5.29 (Germanite)	
SnS_2	*C*6	3.64; 5.87	
SnS	*B*29	3.98; 4.33; 11.18 (Herzenbergite)	
$SnCu_2FeS_4$	$H2_6$	5.46; 10.28 (Stannite)	
PbS	*B*1	5.92 (Galena)	
$PbSnS_2$	*B*29	4.04; 4.28; 11.33 (Teallite)	
AsS	*B*1	9.27; 13.50; 6.56; 106° 37′ (Realgar)	
As_2S_3	*D*5*f*	11.46; 9.56; 4.21; 90° ± 1° (Orpiment)	
FeAsS	$E0_7$	9.6; 5.7; 6.4; ~90° (Arsenopyrite)	
CoAsS	*C*2	5.61 (Cobaltite)	
NiAsS	*C*2	5.66 (Gersdorffite)	
CuAsS	~*B*3 (orthorh.)	3.78; 5.47; 11.47 (Hautite)	
$(Cu, Fe)_3AsS_3$	*B*3	10.2 (Tetrahedrite, Fahlerz)	
Sb_2S_3	$D5_8$	11.3; 11.5; 3.9 (Stibnite)	
FeSbS	$E0_7$	10.00; 5.93; 6.73; ~90° (Gudmundite)	
NiSbS	$F0_1$	5.90 (Ullmannite)	
$CuSbS_2$	$F5_6$	6.01; 3.78; 14.46 (Wolfsbergite)	
$(Cu, Fe)_3$, $(Sb, As)S_3$	*B*3	10.2–10.3 (Tetrahedrite, Fahlerz)	
Bi_2S_3	$D5_8$	11.13; 11.27; 3.97 (Bismuthite)	
$NaBiS_2$	*B*1	5.76	
$KBiS_2$	*B*1	6.01	
$CuBiS_2$	$F5_6$	6.13; 3.89; 14.51 (Emplectite)	
$AgBiS_2$	*B*1	(>210°C), 5.648	
	*B*1 (orthorh. deformed)	(<210°C), 8.08; 7.82; 5.65	
Bi_2Te_2S	*C*33	10.31; 24° 10′ (Tetradymite)	

Table 6.2 STRUCTURAL DETAILS

*A*1 (Cu type)

Cubic: $O_h^5 - Fm3m$; $a = 3.61$; $A = 4$
Co-ordinates: 4Cu(O_h): 000, $\frac{1}{2}\frac{1}{2}0$)

*A*2 (W type)

Cubic: $O_h^9 - Im3m$; $a = 3.16$; $A = 2$
Co-ordinates: 2W(O_h): 000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

*A*3 (Mg type)

Hexagonal: $D_{6h}^4 - P6_3/mmc$; $a = 3.20$, $c = 5.20$; $A = 2$
Co-ordinates: 2Mg(D_{3h}): $\frac{2}{3}\frac{1}{3}0$; $\frac{1}{3}\frac{2}{3}\frac{1}{2}$

*A*4 (Diamond type)

Cubic: $O_h^7 - Fd3m$; $a = 3.56$; $A = 8$
Co-ordinates: 8C(T_d): 000; $\frac{1}{2}\frac{1}{2}0$;) ; $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; $\frac{3}{4}\frac{3}{4}\frac{1}{4}$;)

*A*5 (Tin type)

Tetragonal: $D_{4h}^{19} - I4/amd$; $a = 5.82$, $c = 3.17$; $A = 4$
Co-ordinates: 4Sn(D_{2d}): 000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}0\frac{1}{4}$; $0\frac{1}{2}\frac{3}{4}$

*A*6 (In type)

Tetragonal; $D_{4h}^{17} - F4/mmm$; $a = 4.58$, $c = 4.94$; $A = 4$
Co-ordinates: 4In(D_{4h}): 000; $\frac{1}{2}\frac{1}{2}0$;)

*A*7 (As type)

Rhombohedral: $D_{3d}^5 - R\bar{3}m$
Co-ordinates: Rhombohedral (I), 2As(C_{3v}): $\pm(xxx)$
Rhombohedral (II), 8As(C_{3v}): $(000; \frac{1}{2}\frac{1}{2}0;)\pm(xxx)$
Hexagonal (III), 6As(C_{3v}): $(000; \frac{2}{3}\frac{1}{3}\frac{1}{3}; \frac{1}{3}\frac{2}{3}\frac{2}{3})\pm(00x)$

	Rhomb. I $A=2$		*Rhomb. II* $A=8$		*Hexagonal III* $A=6$			*c/a*
	a	α	*a*	α	*a*	*c*	*x*	
As	4.12	54° 10′	5.57	84° 38′	3.75	10.50	0.226	2.80
Sb	4.50	57° 06′	6.20	87° 24′	4.30	11.24	0.233	2.62
Bi	4.74	57° 14′	6.57	87° 32′	4.54	11.84	0.237	2.61
Simple cub.	—	60°	—	90°	—	—	—	2.45

*A*8 (Se type)

Hexagonal: D_3^4–$P3_121$ (and D_3^6–$P3_221$)
Co-ordinates: 3Se(C_2): $x00$; $\bar{x}\bar{x}\frac{1}{3}$; $0x\frac{2}{3}$ (and $x00$; $\bar{x}\bar{x}\frac{2}{3}$; $0x\frac{1}{3}$)

	a	*c*	*c/a*	*x*
Se	4.36	4.95	1.14	0.22
Te	4.45	5.92	1.33	0.27
Simple cub.	--	-	1.23	0.33

Table 6.2 STRUCTURAL DETAILS—*continued*

A9 (Graphite type)

(α) Hexagonal: $D_{6h}^4-P6_3/mmc$ (if $z=0$); or
$C_{6v}^4-P6_3/mc$ (if $z\neq 0$); $a=2.46$, $c=6.7$; $A=4$
Co-ordinates: $2C(D_{3h}$ or $C_{3v})$: $000; 00\frac{1}{2}$
$2C(D_{3h}$ or $C_{3v})$: $\frac{1}{3}\frac{2}{3}z; \frac{2}{3}\frac{1}{3}(\frac{1}{2}+z)$; $z\approx 0$ (or very probably $z=0$)
(β) Rhombohedral: $D_{3d}^5-R\bar{3}m$; $a=2.46$, $c=10.1$; $A=6$
Co-ordinates: $6C(C_{3v})$: $(000; \frac{2}{3}\frac{1}{3}\frac{1}{3}; \frac{1}{3}\frac{2}{3}\frac{2}{3})\pm(00x)$, with $x\approx\frac{1}{6}$ (or very probably $x=\frac{1}{6}$)

A10 (Hg type)

Rhombohedral: $D_{3d}^5-R\bar{3}m$
Co-ordinates: Rhombohedral (I): $1Hg(D_{3d})$: 000
Rhombohedral (II): $2Hg(D_{3d})$: $000; \frac{1}{2}\frac{1}{2}\frac{1}{2}$
Rhombohedral (III): $4Hg(D_{3d})$: $000; \frac{1}{2}\frac{1}{2}0$;)
Hexagonal (IV): $3Hg(D_{3d})$: $000; \frac{1}{3}\frac{2}{3}\frac{1}{3}; \frac{2}{3}\frac{1}{3}\frac{2}{3}$

	Rhombohedral			*Hexagonal*	*Ideal cubic*			
	I	*II*	*III*	*IV*	*I*	*II*	*III*	*Hex.*
a	3.00	4.90	4.38	3.46	$\frac{a}{2}\sqrt{2}$	$\frac{a}{2}\sqrt{6}$	a	$\frac{a}{2}\sqrt{2}$
α	70° 32′	41° 25′	98° 15′	—	60°	33° 33′	90°	—
c	—	—	—	6.71	—	—	—	$a\sqrt{3}$
A	1	2	4	3	1	2	4	3
c/a	—	—	—	1.94	—	—	—	2.45

A11 (Ga type)

Orthorhombic: $D_{2h}^{18}-Abma$; $a=4.52$, $b=4.51$, $c=7.64$; $A=8$
Co-ordinates: $8Ga(C_s)$: $(000; 0\frac{1}{2}\frac{1}{2})\pm(x0z; \frac{1}{2}+x, \frac{1}{2}, \bar{z})$ with $x=0.079$; $z=0.153$

A12 (α-Mn type)

Cubic: $T_d^3-I\bar{4}3m$; $a=8.89$; $A=58$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2})+2Mn(T_d)$: 000
$+8Mn(C_{3v})$: $xxx; \bar{x}\bar{x}x;$); with $x=0.32$
$+24Mn(C_s)$: $xxz;$) ; $\bar{x}\bar{x}z;$) ; $\bar{x}x\bar{z};$) ; $x\bar{x}\bar{z};$) ; with $x=0.36$; $z=0.04$
$+24Mn(C_s)$ with similar co-ordinates but with $x=0.09$; $z=0.28$

A13 (β-Mn type)

Cubic: O^6-P4_132 and O^7-P4_132; $a=6.30$; $A=20$
Co-ordinates: $8Mn(C_3)$: $xxx; (\frac{1}{2}+x)(\frac{1}{2}-x)\bar{x};$) ; $(\frac{3}{4}-x)(\frac{3}{4}-x)(\frac{3}{4}-x); (\frac{1}{4}-x)(\frac{3}{4}+x)(\frac{1}{4}+x);$) ;
with $x=0.061$
$12Mn(C_2)$: $\frac{3}{8}\bar{x}(\frac{3}{4}+x);$) ; $\frac{7}{8}(\frac{1}{2}+x)(\frac{1}{4}-x);$) ; $\frac{1}{8}x(\frac{1}{4}+x);$) ; $\frac{5}{8}(\frac{1}{2}-x)(\frac{3}{4}-x);$) ;
with $x=0.206$
An alternative structure has been proposed (Wilson[9]) with space group O_h^6-Fm3c; $a=12.58$; $A=160$

A15 (β-W or Cr_3Si type)

Cubic: O_h^3-Pm3n; $a=5.04$ or 4.56; $A=8$
Co-ordinates: $2W$ or $2Si(T_h)$: $000; \frac{1}{2}\frac{1}{2}\frac{1}{2}$
$6W$ or $6Cr(D_{2d})$: $\frac{1}{4}0\frac{1}{2}$;) ; $\frac{3}{4}0\frac{1}{2}$;)

A16 (orh. S type)

Orthorhombic: $D_{2h}^{24}-Fddd$; $a=10.48$, $b=12.92$, $c=24.55$; $A=128$
Co-ordinates: 4 times $32S(C_1)$ in $(000; \frac{1}{2}\frac{1}{2}0;$) $+xyz; \bar{x}\bar{y}z; (\frac{1}{4}-x)(\frac{1}{4}-y)(\frac{1}{4}-z); (\frac{1}{4}+x)(\frac{1}{4}-y)(\frac{1}{4}+z);$
$x\bar{y}\bar{z}; \bar{x}\bar{y}z; (\frac{1}{4}-x)(\frac{1}{4}+y)(\frac{1}{4}+z); (\frac{1}{4}+x)(\frac{1}{4}+y)(\frac{1}{4}-z)$

Table 6.2 STRUCTURAL DETAILS—*continued*

	x	y	z
SI	−0.017	0.083	0.072
SII	−0.094	0.161	0.200
SIII	−0.167	0.105	0.125
SIV	−0.094	0.028	0.250

*A*20 (α-U type)

Orthorhombic: $D_{2h}^{17}-Cmcm$; $a=2.85$, $b=5.87$, $c=4.95$; $A=4$
Co-ordinates: $4U(C_{2v})$: $(000; \frac{1}{2}\frac{1}{2}0)+0y\frac{1}{4}$; $0\bar{y}\frac{3}{4}$; $y=0$, 105

A_a (Pa type)

Tetragonal: $D_{4h}^{17}-I^4/mmm$; $a=3.93$, $c=3.24$; $A=2$
Co-ordinates: $2Pa(D_{4h})$: $000; \frac{1}{2}\frac{1}{2}\frac{1}{2}$

A_b (β-U type)

The structure of pure β-U is not yet known.
It is very similar to β-U with 1.4 at. % Cr contamination.
The structure of such a product has been determined by Tucker[15].
Tetragonal: C_{4v}^4-P4nm; $a=10.52$, $c=5.57$; $A=30$
Co-ordinates: $2U(C_{2v})$: $00z$; $\frac{1}{2}\frac{1}{2}(\frac{1}{2}+z)$; $z=0.66$
$4U(C_s)$: xxz; $\bar{x}\bar{x}z$; $(\frac{1}{2}+x)(\frac{1}{2}-x)(\frac{1}{2}+z)$; $(\frac{1}{2}-x)(\frac{1}{2}+x)(\frac{1}{2}+z)$; $x=0.11$; $z=0.23$
$4U(C_s)$ in similar position with $x=0.32$; $z=0.00$
$4U(C_s)$ in similar position with $x=0.68$; $z=0.50$
$8U(C_1)$: xyz; $\bar{x}\bar{y}z$; $(\frac{1}{2}+x)(\frac{1}{2}-y)(\frac{1}{2}+z)$; $(\frac{1}{2}-x)(\frac{1}{2}+y)(\frac{1}{2}+z)$; xyz; $\bar{y}\bar{x}z$; $(\frac{1}{2}+y)$ $(\frac{1}{2}-x)(\frac{1}{2}+z)$; $(\frac{1}{2}-y)(\frac{1}{2}+x)(\frac{1}{2}+z)$; with $x=0.56$; $y=0.24$; $z=0.25$
$8U(C_1)$ in similar position with $x=0.38$; $y=0.04$; $z=0.20$
Thewlis[14] compared the lattice constants at 720 °C of pure β-U and Cr containing β-U.

	a	c
Pure β-U at 720 °C	10.759	5.656
1.4 at % Cr-U alloy at 720 °C	10.763	5.652
1.4 at % Cr-U alloy at 20 °C	10.590	5.634

A_c (α-Np)

Orthorhombic: $D_{2h}^{16}-Pmcn$; $a=4.72$, $b=4.89$, $c=3.66$; $A=8$
Co-ordinates: $4Np(C_s)$: $\pm(\frac{1}{4}yz)$; $\pm(\frac{1}{4}, \frac{1}{2}-y, \frac{1}{2}+z)$; $y=0.208$; $z=0.036$
$4Np(C_s)$ in similar positions with $y=0.842$; $z=0.319$

A_d (β-Np)

Tetragonal: $D_4^2-P42_1$; $a=4.90$, $c=3.39$; $A=4$
Co-ordinates: $2Np(D_2)$: $000, \frac{1}{2}\frac{1}{2}0$
$2Np(C_4)$: $\frac{1}{2}0z$; $0\frac{1}{2}\bar{z}$; $z=0.38$

A_e (β′-$TiCu_3$ type)

Orthorhombic: $D_{2h}^{17}-Cmcm$; $a=2.59$, $b=4.53$, $c=4.35$; $A=4$
Co-ordinates: 4Ti or $Cu(C_{2v})$: $(000; \frac{1}{2}\frac{1}{2}0)+0y\frac{1}{4}$; $0\bar{y}\frac{3}{4}$; $y=0.345$

A_f ($HgSn_{10}$ type)

Hexagonal: D_{6h}^1-P6/mmm; $a=3.20$, $c=2.98$; $A=1$
Co-ordinates: 1Hg or $Sn(D_{6h})$: 000

Table 6.2 STRUCTURAL DETAILS—*continued*

A_g (B type)

Tetragonal: $D_{2d}^8 - P\bar{4}n2$; $a = 8.73$, $c = 5.03$; $A = 50$
Co-ordinates: 2B(S_4): $00\frac{1}{2}$; $\frac{1}{2}\frac{1}{2}0$
6 times 8B(C_1): xyz; $(\frac{1}{2}-x)(\frac{1}{2}+y)(\frac{1}{2}+z)$
$\bar{x}\bar{y}z$; $(\frac{1}{2}+x)(\frac{1}{2}-y)(\frac{1}{2}+z)$
$\bar{y}x\bar{z}$; $(\frac{1}{2}+y)(\frac{1}{2}+x)(\frac{1}{2}-z)$
$y\bar{x}\bar{z}$; $(\frac{1}{2}-y)(\frac{1}{2}-x)(\frac{1}{2}-z)$

	B I	*B II*	*B III*	*B IV*	*B V*	*B VI*
x	0.328	0.095	0.223	0.078	0.127	0.250
y	0.095	0.328	0.078	0.223	0.127	0.250
x	0.395	0.395	0.105	0.105	0.395	−0.078

A_h (α-Po type)

Cubic: $O_h^1 - Pm3m$; $a = 3.35$; $A = 1$
Co-ordinates: 1Po(O_h): 000

A_i (β-Po)

Rhombohedral: $D_{3d}^5 - R\bar{3}m$; $a = 3.37$; $\alpha = 98°\ 13'$; $A = 1$
Co-ordinates: 1Po(D_{3d}^5): 000

A_k (α-Se)

Monoclinic: $C_{2h}^5 - P2_1/n$; $a = 9.05$, $b = 9.07$, $c = 11.61$; $\beta = 90°\ 46'$; $A = 32$
Co-ordinates: 8 times 4Se(C_1): $\pm(xyz) \pm (\frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2}+z)$

	Se *I*	Se *II*	Se *III*	Se *IV*	Se *V*	Se *VI*	Se *VII*	Se *VIII*
x	0.321	0.427	0.317	0.134	−0.081	−0.156	−0.084	0.131
y	0.486	0.664	0.637	0.820	0.686	0.733	0.520	0.597
z	0.237	0.357	0.535	0.556	0.521	0.328	0.229	0.134

A_l (β-Se)

Monoclinic: $C_{2h}^5 - P2_1/a$; $a = 12.85$, $b = 8.07$, $c = 9.31$; $\beta = 93°\ 08'$; $A = 32$
Co-ordinates: 8 times 4Se(C_1): $\pm(xyz) \pm (\frac{1}{2}+x, \frac{1}{2}-y, z)$

	Se *I*	Se *II*	Se *III*	Se *IV*	Se *V*	Se *VI*	Se *VII*	Se *VIII*
x	0.334	0.227	0.080	0.102	0.159	0.340	0.409	0.459
y	0.182	0.221	0.397	0.578	0.832	0.832	0.763	0.476
z	0.436	0.245	0.238	0.050	0.157	0.141	0.366	0.336

*B*1 (NaCl type)

Cubic: $O_h^5 - Fm3m$; $a = 5.63$; $A = 8$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$; $\frac{1}{2}$)+4Na(O_h): 000
+4Cl(O_h): $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

*B*2 (CsCl type)

Cubic: $O_h^1 - Pm3m$; $a = 4.11$; $A = 2$
Co-ordinates: Cs(O_h): 000; Cl(O_h): $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

Table 6.2 STRUCTURAL DETAILS—*continued*

B3 [Sphalerite (ZnS) type]

Cubic: $T_d^2 - F\bar{4}3m$; $a = 5.42$; $A = 8$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$;) $+4\mathrm{Zn}(T_d)$: 000
$+4\mathrm{S}(T_d)$: $\frac{1}{4}\frac{1}{4}\frac{1}{4}$

B4 [Wurtzite (ZnS) type]

Hexagonal: $C_{6v}^4 - P6_3mc$; $a = 3.81$, $c = 6.23$; $A = 4$
Co-ordinates: $2\mathrm{Zn}(C_{3v})$: $\frac{1}{3}\frac{2}{3}0$; $\frac{2}{3}\frac{1}{3}\frac{1}{2}$
$2\mathrm{S}(C_{3v})$: $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}(\frac{1}{2}+z)$; $z \approx \frac{3}{8}$

B8 (α-NiAs type; β-Ni_2In type)

Between the main types (α) and (β) there exist a number of intermediate arrangements due to the variation of the stoichiometric formulae. The axial ratio c/a may change from the value 1.75 (in type α) to 1.22 (in type β). Similarly, there is virtually a continuous change from the *B8* type to the *C6* type.

α-NiAs type

Hexagonal: $D_{6h}^4 - P6_3/mmc$; $a = 3.61$, $c = 5.03$, $c/a = 1.39$; $A = 4$
Co-ordinates: $2\mathrm{Ni}(D_{3d})$: 000; $00\frac{1}{2}$
$2\mathrm{As}(D_{3h})$: $\frac{1}{3}\frac{2}{3}\frac{1}{4}$; $\frac{2}{3}\frac{1}{3}\frac{3}{4}$

β-Ni_2In type

Hexagonal: $D_{6h}^4 - P6_3/mmc$; $a = 4.19$, $c = 5.15$, $c/a = 1.23$; $A = 6$
$2\mathrm{Ni}(D_{3d})$: 000; $00\frac{1}{2}$; $2\mathrm{Ni}(D_{3h})$: $\frac{1}{3}\frac{2}{3}\frac{3}{4}$; $\frac{2}{3}\frac{1}{3}\frac{1}{4}$
$2\mathrm{In}(D_{3h})$: $\frac{1}{3}\frac{2}{3}\frac{1}{4}$; $\frac{2}{3}\frac{1}{3}\frac{3}{4}$

B9 [Cinnabar (HgS) type]

Hexagonal: $D_3^4 - P3_121$ and $D_3^6 - P3_221$; $a = 4.14$, $c = 9.49$; $A = 6$
Co-ordinates: $3\mathrm{Hg}(C_2)$: $x00$; $\bar{x}\bar{x}\frac{1}{3}$; $0x\frac{2}{3}$; $x = 0.33$
$3\mathrm{S}(C_2)$: $x0\frac{1}{2}$; $\bar{x}\bar{x}\frac{5}{6}$; $0x\frac{1}{6}$; $x = 0.21$

B10 (LiOH type)

Tetragonal: $D_{4h}^7 - P4/nmm$; $a = 3.55$, $c = 4.33$; $A = 4$
Co-ordinates: $2\mathrm{Li}(D_{2d})$: 000; $\frac{1}{2}\frac{1}{2}0$
$2\mathrm{OH}(C_{4v})$: $0\frac{1}{2}z$; $\frac{1}{2}0\bar{z}$; $z = 0.20$
For FeSe: $z = 0.26$

B11 (PbO type)

Tetragonal: $D_{4h}^7 - P4/nmm$; $a = 3.98$, $c = 5.01$; $A = 4$
Co-ordinates: $2\mathrm{Pb}(C_{4v})$: $0\frac{1}{2}z$; $\frac{1}{2}0\bar{z}$; $z = 0.24$
$2\mathrm{O}(C_{4v})$: the same with $z = 0.74$
For γ-TiCu: $z(\mathrm{Ti}) = 0.65$; $z(\mathrm{Cu}) = 0.10$

B13 [Millerite (NiS) type]

Rhombohedral: $C_{3v}^5 - R3m$; $a = 5.64$; $\alpha = 116° 35'$; $A = 6$
Co-ordinates: $3\mathrm{Ni}(C_s)$: xxz;) ; $x = 0$; $z = 0.264$
$3\mathrm{S}(C_s)$: the same with $x = 0.714$; $z = 0.361$

Table 6.2 STRUCTURAL DETAILS—*continued*

*B*16 (GeS type)

Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=4.29$, $b=10.42$, $c=3.64$; $A=8$
Co-ordinates: 4Ge(C_s): $\pm(xy\frac{1}{4})$; $\pm[(\frac{1}{2}-x)(\frac{1}{2}+x)\frac{1}{4}]$; $x=0.167$; $y=0.375$
4S(C_s): the same with $x=0.111$; $y=0.139$

*B*17 [Cooperite (PtS) type]

Tetragonal: $D_{4h}^{9}-P4/mmc$; $a=3.47$, $c=6.12$; $A=4$
Co-ordinates: 2Pt(D_{2h}): $0\frac{1}{2}0$; $\frac{1}{2}0\frac{1}{2}$; 2S(D_{2d}): $00\frac{1}{4}$; $00\frac{3}{4}$

*B*18 [Covellite (CuS) type]

Hexagonal: $D_{6h}^{4}-P6_3/mmc$; $a=3.80$, $c=16.4$; $A=12$
Co-ordinates: 2Cu(D_{3h}): $\pm(\frac{2}{3}\frac{1}{3}\frac{1}{4})$
4Cu(C_{3v}): $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{1}{3}, \frac{2}{3}, \frac{1}{2}-z)$; $z=0.107$
2S(D_{3h}): $\pm(\frac{1}{3}\frac{2}{3}\frac{1}{4})$
4S(C_{3v}): $\pm(00z)$; $\pm(0, 0, \frac{1}{2}-z)$; $z=0.063$

*B*19 (AuCd type)

Orthorhombic: $D_{2h}^{5}-Pmcm$; $a=3.14$, $b=4.85$, $c=4.75$; $A=4$
Co-ordinates: 2Au(C_{2v}): $\pm(0y\frac{1}{4})$; $y=0.805$
2Cd(C_{2v}): $\pm(\frac{1}{2}y\frac{1}{4})$; $y=0.315$
For MgCd: $y(\text{Mg})=0.818$; $y(\text{Cd})=0.323$

*B*20 (FeSi type)

Cubic: T^4-P2_13; $a=4.48$; $A=8$
Co-ordinates: 4Fe(C_3): xxx; $(\frac{1}{2}+x)(\frac{1}{2}-x)\bar{x}$; $\left.\right\}$; $x=0.137$
4Si(C_3): the same with $x=-0.158$
For BeAu: $x(\text{Be})=-0.156$; $x(\text{Au})=0.150$
For RhSn: $x(\text{Rh})=0.142$; $x(\text{Sn})=0.159$

*B*27 (FeB type)

Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=4.05$, $b=5.50$, $c=2.95$; $A=8$
Co-ordinates: 4Fe(C_s): $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.125$; $y=0.180$
4B(C_s): the same with $x=0.61$; $y=0.036$
For MnB: $x(\text{Mn})=0.125$; $y(\text{Mn})=0.180$; $x(\text{B})=0.614$; $y(\text{B})=0.031$
For USi: $x(\text{U})=0.125$; $y(\text{U})=0.180$; $x(\text{Si})=0.611$; $y(\text{Si})=0.028$
For TiB: $x(\text{Ti})=0.123$; $y(\text{Ti})=0.177$; $x(\text{B})=0.603$; $y(\text{B})=0.029$

*B*29 (SnS type)

Orthorhombic: $D_{2h}^{16}-Pmcn$; $a=3.98$, $b=4.33$, $c=11.18$; $A=8$
Co-ordinates: 4Sn(C_s): $\pm(\frac{1}{4}yz)$; $\pm(\frac{1}{4}, \frac{1}{2}-y, \frac{1}{2}+z)$; $y=0.115$; $z=0.118$
4S(C_s): the same with $y=0.478$; $z=0.850$
If this description, given in Strukturbericht vol. 3, p. 14, is transformed to the following, it is virtually identical with the *B*16 (GeS type).
Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=4.33$, $b=11.18$, $c=3.98$; $A=8$
Co-ordinates: 4Sn(C_s): $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.115$; $y=0.382$
4S(C_s): the same with $x=0.022$; $y=0.150$

*B*31 (MnP type)

Orthorhombic: $D_{2h}^{16}-Pcmn$; $a=5.91$, $b=3.17$, $c=5.25$; $A=8$
Co-ordinates: 4Mn(C_s): $\pm(x\frac{1}{4}z)$; $\pm(\frac{1}{2}-x, \frac{1}{4}, \frac{1}{2}+z)$; $x=0.20$; $z=0.005$
4P(C_s): the same with $x=0.57$; $z=0.19$
For AuGa: $x(\text{Au})=0.184$; $z(\text{Au})=0.010$; $x(\text{Ga})=0.590$; $z(\text{Ga})=0.195$

Table 6.2 STRUCTURAL DETAILS—*continued*

For PdSi: $x(\text{Pd})=0.190$; $z(\text{Pd})=0.070$; $x(\text{Si})=0.570$; $z(\text{Si})=0.190$
For PtSi: $x(\text{Pt})=0.195$; $z(\text{Pt})=0.010$; $x(\text{Si})=0.590$; $z(\text{Si})=0.195$
For NiGe: $x(\text{Ni})=0.190$; $z(\text{Ni})=0.005$; $x(\text{Ge})=0.583$; $z(\text{Ge})=0.188$
For PdGe: $x(\text{Pd})=0.188$; $z(\text{Pd})=0.005$; $x(\text{Ge})=0.595$; $z(\text{Ge})=0.190$
For IrGe: $x(\text{Ir})=0.192$; $z(\text{Ir})=0.010$; $x(\text{Ge})=0.590$; $z(\text{Ge})=0.185$
For PtGe: $x(\text{Pt})=0.195$; $z(\text{Pt})=0.010$; $x(\text{Ge})=0.590$; $z(\text{Ge})=0.195$
For PdSn: $x(\text{Pd})=0.182$; $z(\text{Pd})=0.007$; $x(\text{Sn})=0.590$; $z(\text{Sn})=0.182$
For RhSb: $x(\text{Rh})=0.192$; $z(\text{Rh})=0.010$; $x(\text{Sb})=0.590$; $z(\text{Sb})=0.195$
For NiSi: $x(\text{Ni})=0.184$; $z(\text{Ni})=0.006$; $x(\text{Si})=0.580$; $z(\text{Si})=0.170$

*B*32 (NaTl type)

Cubic: O_h^7-Fd3m; $a=7.47$; $A=16$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$;) + 8Na(T_d): 000; $\frac{1}{4}\frac{1}{4}\frac{1}{4}$
+ 8Tl(T_d): $\frac{1}{2}\frac{1}{2}\frac{1}{2}$; $\frac{3}{4}\frac{3}{4}\frac{3}{4}$

*B*34 (PdS type)

Tetragonal: $C_{4h}^2-P4_2/m$; $a=6.43$, $c=6.63$; $A=16$
Co-ordinates: 2Pd(S_4): $00\frac{1}{4}$; $00\frac{3}{4}$; 2Pd(C_{2h}): $0\frac{1}{2}0$; $\frac{1}{2}0\frac{1}{2}$
4Pd(C_s): $\pm(xy0)$; $\pm(\bar{x}y\frac{1}{2})$; $x=0.475$; $y=0.250$
8S(C_1): $\pm(xyz)$; $\pm(xy\bar{z})$; $\pm(y, \bar{x}, \frac{1}{2}+z)$; $\pm(y, \bar{x}, \frac{1}{2}-z)$ with $x=0.20$; $y=0.32$; $z=0.22$

*B*35 (CoSn type)

Hexagonal: D_{6h}^1-P6/mmm; $a=5.27$, $c=4.25$; $A=6$
Co-ordinates: 1Sn(D_{6h}): 000; 2Sn(D_{3h}): $\frac{1}{3}\frac{2}{3}\frac{1}{2}$; $\frac{2}{3}\frac{1}{3}\frac{1}{2}$
3Co(D_{2h}): $\frac{1}{2}00$; $0\frac{1}{2}0$; $\frac{1}{2}\frac{1}{2}0$

*B*37 (TlSe type)

Tetragonal: $D_{4h}^{18}-I4/mcm$; $a=8.02$, $c=7.00$; $A=16$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 4Tl($D_4$): $00\frac{1}{4}$; $00\frac{3}{4}$; + 4Tl(D_{2d}): $\frac{1}{2}0\frac{1}{4}$; $\frac{1}{2}0\frac{3}{4}$
+ 8Se(C_{2v}): $\pm(x, \frac{1}{2}+x, 0)$; $\pm(\frac{1}{2}+x, \bar{x}, 0)$; $x=0.179$

B_a (UCo type)

Cubic: T^5-I2_13; $a=6.36$; $A=16$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 8U($C_3$): xxx; $(\frac{1}{2}+x)(\frac{1}{2}-x)\bar{x}$;) ; $x=0.035$
+ 8Co(C_3): the same with $x=0.294$

B_b(ζ-AgZn type)

Hexagonal: $C_{3i}^1-P\bar{3}$; $a=7.64$; $c=2.82$; $A=9$
Co-ordinates: 1Zn(C_{3i}): 000; + 2Zn(C_3): $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}z$; $z\approx\frac{3}{4}$
(1.5Zn + 4.5Ag) (C_1): $\pm(xyz)$; $\pm(\bar{y}, x-y, z)$; $\pm(y-x, \bar{x}, z)$ with $x=0.350$; $y=0.032$; $z=0.750$

B_c (CaSi type)

Orthorhombic: $D_{2h}^{17}-Cmmc$; $a=3.91$, 4.59, 10.80; $A=8$
Co-ordinates: (000; $0\frac{1}{2}\frac{1}{2}$) + 4Ca(C_{2v}): $\pm(\frac{1}{4}0z)$; $z=0.36$
+ 4Si(C_{2v}): the same with $z=0.07$
By choosing different axes and origin from those given in the original paper, this type becomes virtually identical with the *Bf*(CrB type):
$D_{2h}^{17}-Cmcm$; $a=4.59$, $b=10.80$, $c=3.91$; $y(\text{Ca})=0.14$; $y(\text{Si})=0.43$

Table 6.2 STRUCTURAL DETAILS—*continued*

B_d (η-NiSi)

Orthorhombic: $D_{2h}^{16} - Pbnm$; $a = 5.62$, $b = 5.18$, $c = 3.34$; $A = 8$
Co-ordinates: 4Ni(C_s): $xy0$; $\bar{x}\bar{y}\frac{1}{2}$; $(\frac{1}{2}-x)\ (\frac{1}{2}+y)0$; $(\frac{1}{2}+x)\ (\frac{1}{2}-y)\frac{1}{2}$; $x = 0.184$; $y = 0.006$
4Si(C_s): the same with $x = 0.080$; $y = 0.330$
By choosing different axes and origin from those given in the original paper, this type becomes identical with the $B31$(MnP type):
$D_{2h}^{16} - Pcmn$; $a = 5.62$, $b = 3.34$, $c = 5.18$; x(Ni) = 0.184; z(Ni) = 0.006; x(Si) = 0.580; z(Si) = 0.170

B_e (CdSb type)

Orthorhombic: $D_{2h}^{15} - Pbca$; $a = 6.47$, $b = 8.25$, $c = 8.53$; $A = 16$
Co-ordinates: 8Sb(C_1): $\pm(xyz)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-y, \bar{z})$; $\pm(\bar{x}, \frac{1}{2}+y, \frac{1}{2}-z)$; $\pm(\frac{1}{2}-x, \bar{y}, \frac{1}{2}+z)$
8Cd(C_1): the same

	Sb			Cd *or* Zn		
	x	y	z	x	y	z
CdSb	0.136	0.072	0.108	0.456	0.119	−0.128
ZnSb	0.142	0.081	0.111	0.461	0.103	−0.122

B_f (CrB type)

Orthorhombic: $D_{2h}^{17} - Cmcm$; $a = 2.97$, $b = 7.86$, $c = 2.93$; $A = 8$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0) + 4\text{Cr}(C_{2v})$: $\pm(0y\frac{1}{4})$; $y = 0.146$
$+ 4\text{B}(C_{2v})$: the same with $y = 0.440$
For NbB: y(Nb) = 0.146; y(B) = 0.444
For CaSi: y(Ca) = 0.14; y(Si) = 0.43 (cf. Bc type)

B_g (MoB type)

Tetragonal: $D_{4h}^{19} - I4/amd$; $a = 3.11$, $c = 16.97$; $A = 16$
Co-ordinates: $(000, \frac{1}{2}\frac{1}{2}\frac{1}{2}) + 8\text{Mo}(C_{2v})$: $\pm(00z)$; $\pm(0, \frac{1}{4}, \frac{1}{4}+z)$; $z = 0.197$
$+ 8\text{B}(C_{2v})$: the same with $z = 0.35$

B_h (WC type)

Hexagonal: $D_{6h}^{1} - P6/mmm$; $a = 2.91$, $c = 2.84$; $A = 2$
Co-ordinates: 1W(D_{6h}): 000; 1C(D_{3h}): $\frac{1}{3}\frac{2}{3}0$; $\frac{2}{3}\frac{1}{3}0$

B_i (γ'-MoC type)

Hexagonal: $D_{6h}^{4} - P6_3/mmc$; $a = 2.93$, $c = 10.97$; $A = 8$
Co-ordinates: 4Mo(C_{3h}): $\frac{1}{3}\frac{2}{3}z$; $\frac{1}{3}\frac{2}{3}(\frac{1}{2}-z)$; $\frac{2}{3}\frac{1}{3}(\frac{1}{2}+z)$; $\frac{2}{3}\frac{1}{3}\bar{z}$; $z \approx \frac{1}{8}$
4*C*: in holes

B_k (BN type)

Hexagonal: $D_{6h}^{4} - P6_3/mmc$; $a = 2.50$, $c = 6.66$; $A = 4$
Co-ordinates: 2B(D_{3h}): $\frac{1}{3}\frac{2}{3}\frac{1}{4}$; $\frac{2}{3}\frac{1}{3}\frac{3}{4}$; 2N($D_{3h}$): $\frac{1}{3}\frac{2}{3}\frac{3}{4}$; $\frac{2}{3}\frac{1}{3}\frac{1}{4}$

Table 6.2 STRUCTURAL DETAILS—*continued*

B_l [Realgar (AsS) type]

Monoclinic: $C_{2h}^5 - P2_1n$; $a=9.27$, $b=13.50$, $c=6.56$; $\beta=106°\ 37'$; $A=32$
Co-ordinates: 4 times $4\text{As}(C_1)$ and 4 times $4\text{S}(C_1)$ in:
$\pm(xyz)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-x, \frac{1}{2}+z)$

	As *I*	As *II*	As *III*	As *IV*	S *I*	S *II*	S *III*	S *IV*
x	0.118	0.425	0.318	0.038	0.346	0.213	0.245	0.115
y	0.024	−0.140	−0.127	−0.161	0.008	0.024	−0.225	−0.215
z	−0.241	−0.142	0.181	−0.290	−0.295	0.120	−0.363	0.048

B_m (TiB type)

Orthorhombic: $D_{2h}^{16} - Pnma$; $a=6.12$, $b=3.06$, $c=4.56$; $A=8$
Co-ordinates: $4\text{Ti}(C_s)$: $\pm(x\frac{1}{4}z)$; $\pm(\frac{1}{2}-x, \frac{3}{4}, \frac{1}{2}+z)$; $x=0.177$; $z=0.123$
$4\text{B}(C_s)$: the same with $x=0.029$; $z=0.603$
If the axes are changed from those of the original paper, this type becomes identical with the *B*27 (FeB) type:

$D_{2h}^{16} - Pbnm$; $a=4.56$, $b=6.12$, $c=3.06$; $x(\text{Ti})=0.123$; $y(\text{Ti})=0.177$;
$x(\text{B})=0.603$; $y(\text{B})=0.029$

*C*1 (CaF_2 type—MgAgAs type)

(α) Cubic: $O_h^5 - Fm3m$; $a=5.45$; $A=12$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0; \ldots) + 4\text{Ca}(O_h)$: 000
$+ 8\text{F}(T_d)$: $\pm(\frac{1}{4}\frac{1}{4}\frac{1}{4})$
In those cases in which the *F*-position is occupied by two components in an ordered fashion—for example in As(MgAg)—the space group is changed to
(β) Cubic: $T_d^2 - F\bar{4}3m$; $a=6.24$; $A=12$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0; \ldots) + 4\text{As}(T_d)$: 000
$+ 4\text{Ag}(T_d)$: $\frac{1}{4}\frac{1}{4}\frac{1}{4}$
$+ 4\text{Mg}(T_d)$: $\frac{3}{4}\frac{3}{4}\frac{3}{4}$

*C*2 [Pyrites (FeS_2) type]

Cubic: $T_h^6 - Pa3$; $a=5.40$; $A=12$
Co-ordinates: $4\text{Fe}(S_{3i})$: $000; \frac{1}{2}\frac{1}{2}0; \ldots$
$8\text{S}(C_3)$: $\pm(xxx); \pm(\frac{1}{2}+x, \frac{1}{2}-x, \bar{x}; \ldots)$; $x=0.386$
For MnS_2, $x=0.401$; for CoAsS and NiAsS (random distribution of As and S) $x=0.385$; for $PtBi_2$: $x=0.38$.

*C*6 (CdI_2 type)

Hexagonal: $D_{3d}^3 - P\bar{3}m1$; $a=4.24$; $c=6.84$; $A=3$
Co-ordinates: $1\text{Cd}(D_{3d})$: 000; $2\text{I}(C_{3v})$: $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}\bar{z}$; $z\approx\frac{1}{4}$
There is virtually a continuous change from this type to the *B*8 type.

*C*7 (MoS_2 type)

Hexagonal: $D_{6h}^4 - P6_3/mmc$; $a=3.15$, $c=12.30$; $A=6$
Co-ordinates: $2\text{Mo}(D_{3h})$: $\frac{1}{3}\frac{2}{3}\frac{1}{4}$; $\frac{2}{3}\frac{1}{3}\frac{3}{4}$
$4\text{S}(C_{3v})$: $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}\bar{z}$; $\frac{1}{3}\frac{2}{3}(\frac{1}{2}-z)$; $\frac{2}{3}\frac{1}{3}(\frac{1}{2}+z)$; $z=0.62$

Table 6.2 STRUCTURAL DETAILS—*continued*

*C*11*a* (CaC_2 type)

Tetragonal: $D_{4h}^{17}-I4/mmm$; $a=3.87$, $c=6.37$, $c/a=1.65$; $A=6$
Co-ordinates (000; $\frac{111}{222}$) +2Ca(D_{4h}): 000
+4C(C_{4v}): $\pm(00z)$; $z=0.38$

*C*11*b* ($MoSi_2$ type)

Tetragonal: $D_{4h}^{17}-I/mmm$; $a=3.20$, $c=7.86$, $c/a=2.46$; $A=6$
Co-ordinates: (000; $\frac{111}{222}$) +2Mo(D_{4h}): 000
+4Si(C_{4v}): $\pm(00z)$; $z\approx\frac{1}{3}$
This type is a superstructure of the Aα(Pa) type.

*C*12 ($CaSi_2$ type)

Rhombohedral: $D_{3d}^{5}-R\bar{3}m$; $a=10.4$; $\alpha=21°30'$; $A=6$
Co-ordinates: 2Ca(C_{3v}): $\pm(xxx)$; $x=0.083$
2Si(C_{3v}): the same with $x=0.185$
2Si(C_{3v}): the same with $x=0.352$
Hexagonal axes: $a=3.88$, $c=30.4$; $A=18$
Co-ordinates: (000; $\frac{211}{333}$, $\frac{122}{333}$) +6Ca(C_{3v}): $\pm(00x)$; $x=0.083$
+6Si(C_{3v}): the same with $x=0.185$
+6Si(C_{3v}): the same with $x=0.352$

*C*14 ($MgZn_2$ type)

Hexagonal: $D_{6h}^{4}-P6_3/mmc$; $c=5.15$, $c=8.48$; $A=12$
Co-ordinates: 4Mg(C_{3v}): $\pm(\frac{12}{33}z; \frac{1}{3}, \frac{2}{3}, \frac{1}{2}-z)$; $z\approx\frac{1}{16}=0.062$
2Zn(D_{3d}): 000; 00$\frac{1}{2}$
6Zn(C_{2v}): $\pm(x, 2x, \frac{1}{4}; \bar{2}\bar{x}, \bar{x}, \frac{1}{4}; x\bar{x}\frac{1}{4})$; $x\approx-\frac{1}{6}=-0.170$

*C*15 ($MgCu_2$ type)

Cubic: O_h^7-Fd3m; $a=7.01$; $A=24$
Co-ordinates: (000; $\frac{110}{220}$; $\frac{1}{2}$) +8Mg(T_d): 000; $\frac{111}{444}$
+16Cu(D_{3d}): $\frac{555}{888}$, $\frac{775}{888}$,

*C*16 ($CuAl_2$ type)

Tetragonal: $D_{4h}^{18}-I4/mcm$; $a=6.05$, $c=4.88$; $A=12$
Co-ordinates: (000; $\frac{111}{222}$) +4Cu(D_4): $\pm(00\frac{1}{4})$
+8Al(C_{2v}): $\pm(x, \frac{1}{2}+x, 0; \frac{1}{2}+x, \bar{x}, 0)$; $x=0.158$

	$AuNa_2$	$MnSn_2$	$FeSn_2$	$CoSn_2$	$RhSn_2$	$TiSb_2$	VSb_2	Ta_2B	Mo_2B	W_2B	Mn_2B
x	0.160	0.159	0.160	0.116	0.161	0.158	0.158	0.167	0.170	0.170	0.163

For the compounds $FeGe_2$, (Rh,Pd,Au)Pb_2 no deviation from $x=0.158$ has been reported.

*C*18 [Marcasite (FeS_2) type]

Orthorhombic: $D_{2h}^{12}-Pnnm$; $a=4.44$, $b=5.41$, $c=3.38$; $A=6$
Co-ordinates: 2Fe(C_{2h}): 000; $\frac{111}{222}$
4S(C_s): $\pm(xy0)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2})$; $x=0.20$; $y=0.38$
For $FeAs_2$: $x=0.18$; $y=0.36$
For $NiAs_2$: $x=0.22$; $y=0.37$
For $SeSb_2$: $x=0.18$; $y=0.36$
For FeP_2: $x=0.16$; $y=0.37$
For $CoTe_2$: $x=0.22$; $y=0.36$

Table 6.2 STRUCTURAL DETAILS—*continued*

For $FeTe_2$: $x=0.22$; $y=0.36$
For $FeSe_2$: $x=0.21$; $y=0.37$

*C*22 (Fe_2P type)

Hexagonal: D_3^2-P321; $a=5.85$, $c=3.45$; $A=9$
Co-ordinates: $3Fe(C_2)$: $\bar{x}00$; $0\bar{x}0$; $xx0$; $x=0.26$
$3Fe(C_2)$: $x0\frac{1}{2}$; $0x\frac{1}{2}$; $\bar{x}\bar{x}\frac{1}{2}$; $x=0.40$
$1P(D_3)$: $00\frac{1}{2}$
$2P(C_3)$: $\pm(\frac{1}{3}\frac{2}{3}z)$; $z\approx\frac{1}{8}=0.125$

*C*23 ($PbCl_2$ type)

Orthorhombic: $D_{2h}^{16}-Pmnb$; $a=4.53$, $b=7.61$, $c=9.03$; $A=12$
Co-ordinates: $4Pb(C_s)$: $\pm(\frac{1}{4}yz)$; $\pm(\frac{1}{4}\frac{1}{2}+y, \frac{1}{2}-z)$; $y=0.246$; $z=0.905$
$4Cl(C_s)$: the same with $y=0.85$; $z=0.93$
$4Cl(C_1)$: the same with $y=0.95$; $z=0.33$

For Co_2P, Ni_2Si* and ThS_2 the parameters are:

	P	Co	Co	Th	S	S	Si	Ni	Ni
y	0.250	0.862	0.970	0.250	0.850	0.965	0.236	0.825	0.958
z	0.900	0.930	0.333	0.875	0.942	0.320	0.886	0.937	0.297

*C*32 (AlB_2 type)

Hexagonal: D_{6h}^1-P6/mmm; $a=3.00$, $c=3.25$; $A=3$
Co-ordinates: $1Al(D_{6h})$: 000
$2B(D_{3h})$: $\frac{1}{3}\frac{2}{3}1$, $\frac{2}{3}\frac{1}{3}1$

*C*33 (Bi_2Te_2S type)

Rhombohedral: $D_{3d}^5-R\bar{3}m$; $a=10.31$; $\alpha=24°\,10'$; $A=5$
Co-ordinates: $2Bi(C_{3v})$: $\pm(xxx)$; $x=0.392$
$2Te(C_{3v})$: the same with $x=0.788$
$1S(D_{3d})$: 000

*C*34 [Calaverite ($AuTe_2$) type]

Monoclinic: C_{2h}^3-C2/m; $a=7.18$, $b=4.40$, $c=5.07$; $\beta=90°\,13'$; $A=6$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$) $+2Au(C_{2h})$: 000
$+4Te(C_s)$: $\pm(x0z)$; $x=0.689$; $z=0.280$

*C*36 ($MgNi_2$ type)

Hexagonal: $D_{6h}^4-P6_3/mmc$; $a=4.81$, $c=15.77$; $A=24$
Co-ordinates: $4Mg(C_{3v})$: $+(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{2}{3}, \frac{1}{3}, \frac{1}{2}+z)$; $z\approx\frac{27}{32}$
$4Mg(C_{3v})$: $\pm(00z)$; $\pm(0, 0, \frac{1}{2}+z)$; $z\approx\frac{3}{32}$
$6Ni(C_{2h})$: $\frac{1}{2}00$; $0\frac{1}{2}0$; $\frac{1}{2}\frac{1}{2}0$; $\frac{1}{2}0\frac{1}{2}$; $0\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
$6Ni(C_{2v})$: $\pm(x, 2x, \frac{1}{4}; 2\bar{x}, \bar{x}, \frac{1}{4}; x, \bar{x}, \frac{1}{4})$; $x\approx\frac{1}{6}$
$4Ni(C_{3v})$: $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{2}{3}, \frac{1}{3}, \frac{1}{2}+z)$; $z\approx\frac{1}{8}$

* If Toman's[199] description of δ-Ni_2Si is changed from *Pbnm* to *Pmnb*, and if the origin is chosen differently, this compound belongs to the C23 type.

Table 6.2 STRUCTURAL DETAILS—*continued*

*C*37 (Co_2Si type)

Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=7.10$, $b=4.91$, $c=3.73$; $A=12$
Co-ordinates: $4Si(C_s)$: $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.440$; $y=0.070$
$4Co(C_s)$: the same with $x=0.103$; $y=0.090$
$4Co(C_s)$: the same with $x=0.772$; $y=0.193$
With a different choice of axes and origin, a similarity to the *C*23 ($PbCl_2$ type) becomes apparent:
Orthorhombic: $D_{2h}^{16}-Pmnb$; $a=3.73$, $b=4.91$, $c=7.10$; $A=12$

Co-ordinates: $4Si(C_s)$: $\pm(\frac{1}{4}yz)$; $\pm(\frac{1}{4}, \frac{1}{2}+y, \frac{1}{2}-z)$; $y=0.07$; $z=0.94$
$4Co(C_s)$: the same with $y=0.59$; $z=0.897$
$4Co(C_s)$: the same with $y=0.693$; $z=0.228$
With this orientation the lattice constants are virtually identical with those of δ-Ni_2Si ($a=3.73$, $b=4.99$, $c=7.03$) which has the *C*23 type. A redetermination of the Co_2Si type might lead to a still closer similarity than that appearing in this description.

*C*38 (Cu_2Sb type)

Tetragonal: $D_{4h}^{7}-P4/nmm$; $a=3.99$, $c=6.09$; $A=6$
Co-ordinates: $2Cu(D_{2d})$: $000, \frac{11}{22}0$
$2Cu(C_{4v})$: $0\frac{1}{2}z; \frac{1}{2}0\bar{z}$; $z=0.27$
$2Sb(C_{4v})$: the same with $z=0.70$

For $Cu_{2-x}Te$; $z(Cu)=0.27$; $z(Te)=0.715$, with vacant sites in the $(0\frac{1}{2}z)$-position.
For Fe_2As and Cr_2As: $z(As)=0.735$; $z(Fe$ or $Cr)=0.33$. For CuMgAs: $z(As)=0.75$; $z(Cu, Mg)=0.335$. For $AlNaSi_4$: $z(Si)=0.79$; $z(Na, Al)=0.37$.

A very similar arrangement is shown by $CuGa_2$ with $a=2.83$, $c=5.84$. The 3 atoms per cell take the positions 000; $\frac{11}{22}x$; $\frac{11}{22}y$ with $x=0.70$; $y=0.27$. For comparison a larger cell with $a'=a\sqrt{2}$ can be chosen:

Tetragonal: $C_{4v}^{1}-P4mm$; $a'=4.03$, $c=5.84$; $A=6$
Co-ordinates: $2Ga(C_{4v})$: $000; \frac{11}{22}0$
$2Ga(C_{4v})$: $0\frac{1}{2}z; \frac{1}{2}0z$; $z=0.70$
$2Cu(C_{4v})$: $0\frac{1}{2}z; \frac{1}{2}0z$; $z=0.27$

*C*40 ($CrSi_2$ type)

Hexagonal: D_6^4 (or D_6^5)$-P6_222$ (or $P6_422$); $a=4.42$, 6.35; $A=9$
Co-ordinates: $3Cr(D_2)$: $\frac{1}{2}00; \frac{111}{223}; 0\frac{12}{23}$
$6Si(C_2)$: $\pm(x, 2x, 0); x\bar{x}\frac{1}{3}; \bar{x}x\frac{1}{3}; 2x, x, \frac{2}{3}; 2\bar{x}, \bar{x}\frac{2}{3}$; $x\approx\frac{1}{6}$

*C*42 (SiS_2 type)

Orthorhombic: $D_{2h}^{26}-Icma$; $a=5.60$, $b=5.53$, $c=9.55$; $A=12$
Co-ordinates: $(000, \frac{111}{222})$ $+4Si(D_2)$: $\pm(0\frac{1}{4}0)$
$+8S(C_s)$: $\pm(x0z)$; $\pm(x\frac{1}{2}\bar{z})$; $x=0.208$; $z=0.119$

*C*44 (GeS_2 type)

Orthorhombic: $C_{2v}^{19}-Fdd$; $a=11.66$, $b=22.34$, $c=6.86$; $A=72$
Co-ordinates: $(000; \frac{11}{22}0;$) $+8Ge(C_2)$: $000; \frac{111}{444}$
$+16Ge(C_1)$: xyz; $\bar{x}\bar{y}z$; $(\frac{1}{4}-x)(\frac{1}{4}+y)(\frac{1}{4}+z)$; $(\frac{1}{4}+x)(\frac{1}{4}-y)(\frac{1}{4}+z)$ with $x=0.125$; $y=0.139$; $z=0.00$
$+16S(C_1)$: the same with $x=0.022$; $y=0.081$; $z=0.183$
$+16S(C_1)$: the same with $x=0.153$; $y=-0.014$; $z=-0.183$
$+16S(C_1)$: the same with $x=0.063$; $y=0.125$; $z=-0.278$

*C*46 [Krennerite ($AuTe_2$) type]

Orthorhombic: $C_{2v}^{4}-Pma$; $a=16.54$, $b=8.82$, $c=4.46$; $A=24$
Co-ordinates: $2Au(C_2)$: $00z; \frac{1}{2}0z$; $z=0$

Table 6.2 STRUCTURAL DETAILS—*continued*

2Au(C_s): $\frac{1}{4}yz$; $\frac{3}{4}\bar{y}z$; $y=0.319$; $z=0.014$
4Au(C_1): xyz; $\bar{x}\bar{y}z$; $(\frac{1}{2}-x)yz$; $(\frac{1}{2}+x)\bar{y}z$; $x=0.124$; $y=0.666$; $z=0.500$
2Te(C_s): $\frac{1}{4}yz$; $\frac{3}{4}\bar{y}z$; $y=0.018$; $z=0.042$
2Te(C_s): the same with $y=0.617$; $z=0.042$
4Te(C_1): as 4Au (C_1) with $x=0.003$; $y=0.699$; $z=0.042$
4Te(C_1): the same with $x=0.132$; $y=0.364$; $z=0.500$
4Te(C_1): the same with $x=0.119$; $y=0.964$; $z=0.500$

*C*49 ($ZrSi_2$ type)

Orthorhombic: $D_{2h}^{17}-Cmcm$; $a=3.72$, $b=14.61$, $c=3.67$; $A=12$
Co-ordinates: (000; $\frac{11}{22}0$) +4Zr(C_{2v}): $\pm(0y\frac{1}{4})$; $y=0.106$
+4Si(C_{2v}): the same with $y=0.750$
+4Si(C_{2v}): the same with $y=0.355$

*C*54 ($TiSi_2$ type)

Orthorhombic: $D_{2h}^{24}-Fddd$; $a=8.24$, $b=4.77$, $c=8.52$; $A=24$
Co-ordinates: (000, $\frac{11}{22}0$;) +8Ti(D_2): 000; $\frac{111}{444}$
+16Si(C_2): $\pm(x00)$; $(\frac{1}{4}+x)\frac{11}{44}$; $(\frac{1}{4}-x)\frac{11}{44}$; $x\approx\frac{1}{3}$

C_a(Mg_2Ni type)

Hexagonal: $D_6^4(D_6^5)-P6_222(P6_422)$; $a=5.18$, $c=13.19$; $A=18$
Co-ordinates: 3Ni(D_2): $00\frac{1}{6}$; $00\frac{3}{6}$; $00\frac{5}{6}$
3Ni(D_2): $0\frac{1}{2}\frac{1}{6}$; $\frac{1}{2}0\frac{3}{6}$; $\frac{11}{22}\frac{5}{6}$
6Mg(C_2): $\pm(\frac{1}{2}0z)$, $\frac{11}{22}(\frac{1}{3}+z)$; $\frac{11}{22}(\frac{1}{3}-z)$; $0\frac{1}{2}(\frac{2}{3}+z)$; $0\frac{1}{2}(\frac{2}{3}-z)$; $z=\frac{1}{9}$
6Mg(C_2): $\pm(x, 2x, 0)$; $x\bar{x}\frac{1}{3}$; $\bar{x}x\frac{1}{3}$; $2x, x, \frac{2}{3}$; $2\bar{x}, \bar{x}\frac{2}{3}$; $x=\frac{1}{6}$

C_b(Mg_2Cu type)

Orthorhombic: $D_{2h}^{24}-Fddd$; $a=5.27$, $b=9.05$, $c=18.21$; $A=48$
Co-ordinates: (000; $\frac{11}{22}0$;) +16Cu(C_2): $\pm(00z)$; $\frac{11}{44}(\frac{1}{4}+z)$; $\frac{11}{44}(\frac{1}{4}-z)$; $z=0.128$
+16Mg(C_2): the same with $z=0.411$
+16Mg(C_2): $\pm(0y0)$; $\frac{1}{4}(\frac{1}{4}+y)\frac{1}{4}$; $\frac{1}{4}(\frac{1}{4}-y)\frac{1}{4}$; $y=0.161$

C_c($ThSi_2$ type)

Tetragonal: $D_{4h}^{19}-I4/amd$; $a=4.13$, $c=14.35$; $A=12$
Co-ordinates: (000; $\frac{11}{22}\frac{1}{2}$) +4Th(D_{2d}): 000; $0\frac{1}{2}\frac{1}{4}$
+8Si(C_{2v}): $\pm(00z)$; $0\frac{1}{2}(\frac{1}{4}+z)$; $0\frac{1}{2}(\frac{1}{4}-z)$; $z=0.417$

C_e($CoGe_2$ type)

Orthorhombic: $C_{2v}^{17}-Aba$; $a\approx b=5.67$, $c=10.80$; $A=24$
Co-ordinates: (000, $0\frac{11}{22}$) +4Co(C_2): $00z$; $\frac{11}{22}z$; $z=-0.012$
+4Co(C_2): the same with $z=-0.238$
+8Ge(C_1): xyz; $\bar{x}\bar{y}z$; $(\frac{1}{2}-x)(\frac{1}{2}+y)z$; $(\frac{1}{2}+x)(\frac{1}{2}-y)z$; with $x=0.342$; $y=0.158$; $z=-\frac{1}{8}$
+8Ge(C_1): the same with $x=y=\frac{1}{4}$; $z=\frac{1}{8}$

The real composition is $Co_{0.9}Ge_2$.

C_f

Tetragonal: a series of types composed of alternating sheets of the Fluorite—and the *C*16(Al_2Cu)—type. Whereas the length of the *a*-axis is approximately constant, the length of the *c*-axis varies due to the different possibilities of the sheet sequences.

Table 6.2 STRUCTURAL DETAILS—*continued*

	$RhSn_2$	$PdSn_2$
a	6.38	6.55
c	17.88	24.57

C_g(ThC_2 type)

Monoclinic: $C^6_{2h}-C2/c$; $a=6.53$, $b=4.24$, $c=6.56$; $\beta=104°$; $A=12$
Co-ordinates: (000; $\frac{11}{22}0$) $+4Th(C_2)$: $\pm(0y\frac{1}{4})$; $y=0.202$
$+8C(C_1)$: $\pm(xyz)$; $\pm(x, \bar{y}, \frac{1}{2}+z)$; with $x=0.29$; $y=0.13$; $z=0.08$

C_h(Cu_2Te type)

Hexagonal: $D^1_{6h}-P6/mmm$; $a=4.24$, $c=7.27$; $A=6$
Co-ordinates: $2Te(C_{6v})$: $\pm(00z)$; $z=0.306$
$4Cu(C_{3v})$: $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{1}{3}\frac{2}{3}\bar{z})$; $z=0.160$

C_k(~ $LiZn_2$ type)

Hexagonal: $D^4_{6h}-P6_3/mmc$; $a=4.36$, $c=2.51$; $A\approx3$
Co-ordinates: $2Zn(D_{3h})$: $\pm(\frac{1}{3}\frac{2}{3}\frac{1}{4})$
$0.8Li(D_{3d})$: 000; $00\frac{1}{2}$; (?)

$D0_2$($CoAs_3$ type)

Cubic: T^5_h-Im3; $a=8.18$; $A=32$
Co-ordinates: (000; $\frac{11}{22}\frac{1}{2}$) $+8Co(C_{3i})$: $\frac{1}{4}\frac{1}{4}\frac{1}{4}$, $\frac{3}{4}\frac{3}{4}\frac{1}{4}$;)
$+24As(C_s)$: $\pm(xy0;\)$ $\pm(x\bar{y}0;\)$; $x=0.35$; $y=0.15$

$D0_3$(BiF_3 or $BiLi_3$ type)

Cubic: O^5_h-Fm3m; for $BiLi_3$: $a=6.71$; $A=16$
Co-ordinates: (000; $\frac{11}{22}0$;) $+4Bi(O_h)$; 000
$+4Li(O_h)$; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
$+8Li(T_d)$: $\pm(\frac{1}{4}\frac{1}{4}\frac{1}{4})$

$D0_9$(ReO_3 or Cu_3N type)

Cubic: O^1_h-Pm3m; for Cu_3N; $a=3.81$; $A=4$
Co-ordinates: $1N(O_h)$: 000; $3Cu(D_{4h})$: $\frac{1}{2}00$;

$D0_{11}$(Fe_3C type)

Orthorhombic: $D^{16}_{2h}-Pbnm$; $a=4.51$, $b=5.08$, $c=6.73$; $A=16$
Co-ordinates: $4Fe(C_s)$: $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.833$; $y=0.040$
$8Fe(C_1)$: $\pm(xyz)$; x, y, $\frac{1}{2}-z$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, z; \frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{2}-z)$;
$x=0.333$; $y=0.183$; $z=0.065$
$4C(C_s)$: $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.47$; $y=0.86$

$D0_{18}$(Na_3As type)

Hexagonal: $D^4_{6h}-P6_3/mmc$; $a=5.09$, $c=8.98$; $A=8$
Co-ordinates: $2As(D_{3h})$: $\pm(\frac{1}{3}\frac{2}{3}\frac{1}{4})$
$2Na(D_{3h})$: $\pm(00\frac{1}{4})$
$4Na(C_{3v})$: $\pm(\frac{1}{3}\frac{2}{3}z; \frac{2}{3}, \frac{1}{3}, \frac{1}{2}+z)$; $z=0.583$

$D0_{19}$(Mg_3Cd type)

Hexagonal: $D^4_{6h}-P6_3/mmc$; $a=6.26$, $c=5.07$; $A=8$
Co-ordinates: $2Cd(D_{3h})$: $\pm(\frac{1}{3}\frac{2}{3}\frac{1}{4})$
$6Mg(C_{2v})$: $\pm(2x, x, \frac{1}{4}; \bar{x}x\frac{1}{4}; \bar{x}, 2x, \frac{1}{4})$; $x\approx\frac{1}{6}$

Table 6.2 STRUCTURAL DETAILS—*continued*

$D0_{20}$($NiAl_3$ type)

Orthorhombic: $D_{2h}^{16}-Pnma$; $a=6.60$, $b=7.35$, $c=4.80$; $A=16$
Co-ordinates: 4Ni(C_s): $\pm(x\frac{1}{4}z)$; $\pm(\frac{1}{2}+x, \frac{1}{4}, \frac{1}{2}-z)$; $x=-0.731$; $z=-0.055$
4Al(C_s): the same with $x=0.011$; $z=0.415$
8Al(C_1): $\pm(xyz)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2}-z)$; $\pm(x, \frac{1}{2}-y, z)$; $\pm(\frac{1}{2}+x, y, \frac{1}{2}-z)$ with $x=0.174$; $y=0.053$; $z=0.856$

Following the choice of co-ordinates and of the origin in the original paper, $NiAl_3$ was described in the Strukturbericht as a separate type. However, another choice of co-ordinates and of origin shows that the structure is very similar to the $D0_{11}$(Fe_3C) type:
Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=4.80$, $b=6.60$, $c=7.35$; $A=16$
Co-ordinates: 4Al(C_s): $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.915$; $y=0.011$
8Al(C_1): $\pm(xyz, xy\frac{1}{2}-z)$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, z; \frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{2}-z)$; $x=0.356$; $y=0.174$; $z=0.053$
4Ni(C_s): $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.445$; $y=0.869$

$D0_{21}$(Cu_3P type)

Hexagonal: $D_{3d}^{4}-P\bar{3}c1$; $a=7.07$, $c=7.14$; $A=24$
Co-ordinates: 6P(C_2): $\pm(x0\frac{1}{4})$; $\pm(0x\frac{1}{4})$; $\pm(\bar{x}\bar{x}\frac{1}{4})$; $x=0.38$
2Cu(C_{3i}): $000, 00\frac{1}{2}$
4Cu(C_3): $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{1}{3}, \frac{2}{3}, \frac{1}{2}+z)$; $z=0.17$
12Cu(C_1): $\pm[xyz; \bar{y}(x-y)z; (y-x)\bar{x}z; \bar{y}\bar{x}(\frac{1}{2}+z); x(x-y)(\frac{1}{2}+z); (x-y)y(\frac{1}{2}+x)]$; $x=0.69$; $y=0.07$; $z=0.08$

See remarks by Haraldsen[200]

$D0_{22}$($TiAl_3$ type)

Tetragonal: $D_{4h}^{17}-I4/mmm$; $a=3.84$, $c=8.58$; $A=8$
Co-ordinates: $(000; \frac{111}{222})$ +2Ti(D_{4h}): 000
+2Al(D_{4h}): $00\frac{1}{2}$
+Al(D_{2d}): $0\frac{11}{24}; \frac{1}{2}0\frac{1}{4}$

$D0_{23}$($ZrAl_3$ type)

Tetragonal: $D_{4h}^{17}-I4/mmm$; $a=4.01$, $c=17.29$; $A=16$
Co-ordinates: $(000; \frac{111}{222})$ +4Zr(C_{4v}): $\pm(00z)$; $z=0.122\approx\frac{1}{8}$
+4Al(D_{2h}): $0\frac{1}{2}0; \frac{1}{2}00$
+4Al(D_{2d}): $0\frac{11}{24}; \frac{1}{2}0\frac{1}{4}$
+4Al(C_{4v}): $\pm(00z)$; $z=0.361\approx\frac{3}{8}$

$D0_{24}$($TiNi_3$ type)

Hexagonal: $D_{6h}^{4}-P6_3/mmc$; $a=5.10$, $c=8.30$; $A=16$
Co-ordinates: 2Ti(D_{3d}): $000; 00\frac{1}{2}$; 2Ti(D_{3h}): $\frac{12}{33}\frac{1}{4}; \frac{21}{33}\frac{3}{4}$
6Ni(C_{2h}): $\frac{1}{2}00; 0\frac{1}{2}0; \frac{1}{2}\frac{1}{2}0; \frac{1}{2}0\frac{1}{2}; 0\frac{11}{22}; \frac{111}{222}$
6Ni(C_{2v}): $\pm(x, 2x\frac{1}{4}; 2\bar{x}, \bar{x}, \frac{1}{4}; x\bar{x}\frac{1}{4})$; $x=\approx-\frac{1}{6}$

$D0_a$(β-$TiCu_3$ type)

Orthorhombic: $D_{2h}^{13}-Pmmn$; $a=5.15$, $b=4.34$, $c=4.52$; $A=8$
Co-ordinates: 2Ti(C_{2v}): $00z; \frac{11}{22}\bar{z}$; $z=0.655$
2Cu(C_{2v}): $0\frac{1}{2}z; \frac{1}{2}0\bar{z}$; $z=0.345$
4Cu(C_s): $x0z; \bar{x}0z; (\frac{1}{2}+x)\frac{1}{2}\bar{z}; (\frac{1}{2}-x)\frac{1}{2}\bar{z}$; $x=\frac{1}{4}$; $z=0.155$

$D0_b$(γ-Ag_3Ga type)

Hexagonal: $C_{3i}^{1}-P\bar{3}$; $a=7.80$, $c=2.88$; $A=9$
Co-ordinates: 2Ga(C_3): $\frac{12}{23}z; \frac{21}{33}\bar{z}$; $z\approx\frac{1}{4}$
6Ag(C_1): $\pm(xyz)$; $\pm(\bar{y}, x-y, z)$; $\pm(y-x, \bar{x}, z)$; $x\approx\frac{1}{3}$; $y\approx\frac{1}{3}$; $z\approx\frac{1}{4}$
1(Ag, Ga)(C_{3i}): 000

Table 6.2 STRUCTURAL DETAILS—*continued*

$D0_c$ (U_3Si type)

Tetragonal: $D_{4h}^{18} - I4/mcm$; $a = 6.02, 8.70$; $A = 16$
Co-ordinates: (000; $\frac{111}{222}$ + 4U(D_4): $\pm(00\frac{1}{4})$
+8U(C_{2v}): $\pm(x, \frac{1}{2}+x, 0)$; $\pm(\frac{1}{2}+x, \bar{x}, 0)$; $x = 0.231$
+4Si(D_{2d}): $0\frac{11}{24}$; $\frac{1}{2}0\frac{1}{4}$

$D0_d$ (Mn_3As type)

Orthorhombic: $D_{2h}^{13} - Pmmn$; $a \approx b = 3.78$, $c = 16.26$; $A = 16$
Co-ordinates: 3 times 2Mn(C_{2v}): $00z$; $\frac{11}{22}z$;
2As(C_{2v}): the same
3 times 2Mn(C_{2v}): $0\frac{1}{2}z$; $\frac{1}{2}0\bar{z}$;
2As (C_{2v}): the same

	(00z)-*position*				(0½z)-*position*			
	Mn *I*	Mn *II*	Mn *III*	As *I*	Mn *IV*	Mn *V*	Mn *VI*	As *II*
z	0.194	−0.194	−0.435	0.409	0.307	−0.307	−0.066	0.091

$D1_3$ ($BaAl_4$ type)

Tetragonal: $D_{4h}^{17} - I4/mmm$; $a = 4.53$, $c = 11.14$; $A = 10$
Co-ordinates: (000; $\frac{111}{222}$) +2Ba(D_{4h}): 000
+4Al(C_{4v}): $\pm(00z)$; $z = 0.380$
+Al(D_{2d}); $0\frac{11}{24}$; $\frac{1}{2}0\frac{1}{4}$

$D1_a$ ($MoNi_4$ type)

Tetragonal: $C_{4h}^5 - I_4/m$; $a = 5.73$, $c = 3.55$; $A = 10$
Co-ordinates: (000, $\frac{111}{222}$) +2Mo(C_{4h}): 000
+8Ni(C_s): $\pm(xy0)$; $\pm(y\bar{x}0)$; $x = 0.400$; $y = 0.200$

$D1_b$ (UAl_4 type)

Orthorhombic: C_{2v}^{20} (or D_{2h}^{28}) $- I2ma$ (*or* $Imma$); $a = 4.41$, $b = 6.27$, $c = 13.71$; $A = 20$
Co-ordinates: (000; $\frac{111}{222}$) +4U(C_{2v}): $\pm(0\frac{1}{4}z)$; $z = 0.111$
+4Al(C_{2v}): the same with $z = -0.111$
+4Al(C_{2h}): 000, $0\frac{11}{22}$
+8Al(C_s): $\pm(0yz)$; $\pm(0, \frac{1}{2}-y, z)$; $y = -0.033$; $z = 0.314$

$D1_c$ ($PtSn_4$ type)

Orthorhombic: $C_{2v}^{17} - Aba2$; $a = 6.38$, $b = 6.41$, $c = 11.33$; $A = 20$
Co-ordinates: (000; $0\frac{11}{22}$) +4Pt(C_2): $00z$; $\frac{11}{22}z$; $z = 0$
+2 times 8Sn(C_1): xyz; $\bar{x}\bar{y}z$; $(\frac{1}{2}+x)(\frac{1}{2}-y)z$; $(\frac{1}{2}-x)(\frac{1}{2}+y)z$

	x	*y*	*z*
Sn I	0.173	0.327	0.125
Sn II	0.33	0.17	−0.13

$D1_d$ ($PtPb_4$ type)

Tetragonal: $D_{4h}^3 - P4/nbm$; $a = 6.65$, $c = 5.97$; $A = 10$
Co-ordinates: 2Pt(D_4): 000; $\frac{11}{22}0$
8Pb(C_s): $x(\frac{1}{2}+x)z$; $\bar{x}(\frac{1}{2}-x)z$; $(\frac{1}{2}+x)\bar{x}z$; $(\frac{1}{2}-x)xz$; $x(\frac{1}{2}-x)\bar{z}$; $\bar{x}(\frac{1}{2}+x)\bar{z}$; $(\frac{1}{2}+x)x\bar{z}$;
$(\frac{1}{2}-x)\bar{x}\bar{z}$; $x = 0.175$; $z = 0.255$

Table 6.2 STRUCTURAL DETAILS *continued*

$D1_e$ (UB_4 type)

Tetragonal: $D_{4h}^5 - P4/mbm$; $a = 7.08$, $c = 3.98$; $A = 20$
Co-ordinates: $4U(C_{2v})$: $\pm(x, \frac{1}{2}+x, 0; \frac{1}{2}+x, \bar{x}, 0)$; $x = 0.31$
$4B(C_4)$: $\pm(00z; \frac{1}{2}\frac{1}{2}z)$; $z = 0.2$
$4B(C_{2v})$: $\pm(x, \frac{1}{2}+x, \frac{1}{2}; \frac{1}{2}+x, \bar{x}, \frac{1}{2})$; $x = 0.1$
$4B(C_s)$: $\pm[xy\frac{1}{2}; y\bar{x}\frac{1}{2}; (\frac{1}{2}+x)(\frac{1}{2}-y)\frac{1}{2}; (\frac{1}{2}+y)(\frac{1}{2}+x)\frac{1}{2}]$ $x = 0.2$; $y = 0.04$

$D1_f$ (Mn_4B type)

Orthorhombic: $D_{2h}^{24} - Fddd$; $a = 14.53$, $b = 7.29$, $c = 4.21$; $A = 40$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0; \text{ }) + 16Mn(C_2)$: $\pm(0y0); \frac{1}{4}(\frac{1}{4}+y)\frac{1}{4}; \frac{1}{4}(\frac{1}{4}-y)\frac{1}{4}$; $y = 0.333$
$+16Mn(C_2)$: $\pm(x00); (\frac{1}{4}+x)\frac{1}{4}\frac{1}{4}; (\frac{1}{4}-x)\frac{1}{4}\frac{1}{4}$; $x = 0.083$
$+8B(C_2)$: at random in the same position with $x = 0.375$

$D1_g$ (B_4C type)

Rhombohedral: $D_{3d}^5 - R\bar{3}m$; $a = 5.19$; $\alpha = 66°\ 18'$; $A = 15$
(Hexagonal setting: $a = 5.60$, $c = 12.12$; $A = 45$)
Co-ordinates: $(000; \frac{2}{3}\frac{1}{3}; \frac{2}{3}\frac{1}{3}) + 3C(D_{3d})$: $00\frac{1}{2} + 6C(C_{3v})$: $\pm(00z)$; $z = 0.385$
$+18B(C_1)$: $\pm(x\bar{x}z)$; $\pm(x, 2x, z)$; $\pm(2\bar{x}, \bar{x}, z)$; $x = 0.106$; $z = 0.113$
$+18B(C_1)$: the same with $x = \frac{1}{6}$; $z = 0.360$

$D2_1$ (CaB_6 type)

Cubic: $O_h^1 - Pm3m$; $a = 4.15$; $A = 7$
Co-ordinates: $1Ca(O_h)$: 000
$6B(C_{4v})$: $\pm(\frac{1}{2}\frac{1}{2}x; \text{ })$; $x = 0.20$

$D2_3$ ($NaZn_{13}$ type)

Cubic: $O_h^6 - Fm3c$; $a = 12.27$; $A = 112$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0; \text{ }) + 8Na(O)$: $\pm(\frac{1}{4}\frac{1}{4}\frac{1}{4})$
$+8Zn(T_h)$: $000; \frac{1}{2}\frac{1}{2}\frac{1}{2}$
$+96Zn(C_s)$: $\pm(0yz; \text{ }; \frac{1}{2}zy; \text{ }; 0y\bar{z}; \text{ }; \frac{1}{2}\bar{z}y; \text{ })$; $y = 0.1806$; $z = 0.1192$

For $Be_{13}U$, neutron diffraction gave: $y = 0.178$; $z = 0.112$

$D2_a$ ($TiBe_{12}$ type)

Hexagonal: $a = 29.44$, $c = 7.33$; $A = 624$ (637?)

The structure shows a particular type of disorder that cannot yet be explained in detail. The approximate structure of a pseudocell was determined (Raeuchle and Rundle[201]):

Hexagonal: $D_{6h}^1 - P6/mmm$; $a = 4.23$, $c = 7.33$; $A = 13$
Co-ordinates: $1Ti(D_{6h})$: in (000) or in $(00\frac{1}{2})$
$2Be(C_{6v})$: $\pm(00z)$; $z \approx \frac{1}{4}$
$2Be(D_{3d})$: $\frac{1}{3}\frac{2}{3}0$; $\frac{2}{3}\frac{1}{3}0$; $2Be(D_{3d})$: $\frac{1}{3}\frac{2}{3}\frac{1}{2}$; $\frac{2}{3}\frac{1}{3}\frac{1}{2}$
$6Be(C_{2v})$: $\pm(\frac{1}{2}0z)$; $\pm(0\frac{1}{2}z)$; $\pm(\frac{1}{2}\frac{1}{2}z)$

$D2_h$ ($ThMn_{12}$ type)

Tetragonal: $D_{4h}^{17} - I4/mmm$; $a = 8.74$, 4.95; $A = 26$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2}) + 2Th(D_{4h})$: 000
$+8Mn(C_{2h})$: $\frac{1}{4}\frac{1}{4}\frac{1}{4}$, $\frac{3}{4}\frac{3}{4}\frac{1}{4}$;
$+8Mn(C_{2v})$: $\pm(x00)$; $\pm(0x0)$; $x = 0.361$
$+8Mn(C_{2v})$: $\pm(x\frac{1}{2}0)$; $\pm(\frac{1}{2}x0)$; $x = 0.277$

Table 6.2 STRUCTURAL DETAILS—*continued*

$D2_c$ (U_6Mn type)

Tetragonal: $D_{4h}^{18}-I4/mcm$ (or subgroup); $a=10.29$, $b=5.24$; $A=28$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$)+4Mn($D_4$): $\pm(00\frac{1}{4})$
+8U(C_{2v}): $\pm(x, \frac{1}{2}+x, 0)$; $\pm(\frac{1}{2}+x, \bar{x}, 0)$; $x=0.405$
+16U(C_s): $\pm(xy0; y\bar{x}0; x\bar{y}\frac{1}{2}; yx\frac{1}{2})$; $x=0.213$; $y=0.103$

$D2_d$ ($CaCu_5$ type)

Hexagonal: $D_{6h}^{1}-C6/mmm$; $a=5.10$, $c=4.08$; $A=6$
Co-ordinates: 1Ca(D_{6h}): 000
2Cu(D_{3h}): $\frac{1}{3}\frac{2}{3}0$; $\frac{2}{3}\frac{1}{3}0$; 3Cu(D_{2h}): $\frac{1}{2}0\frac{1}{2}$; $0\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

$D2_e$ ($BaHg_{11}$ type)

Cubic: O_h^1-Pm3m; $a=9.60$; $A=36$
Co-ordinates: 3Ba(D_{4h}): $\frac{1}{2}00$;)
1Hg(O_h): 000; 8Hg (C_{3v}): $\pm(xxx; xx\bar{x};$); $x=0.155$
12Hg(C_{2v}): $\pm(xx0;$); $\pm(x\bar{x}0;$); $x=0.345$
12Hg(C_{2v}): $\pm(xx\frac{1}{2};$); $\pm(x\bar{x}\frac{1}{2};$); $x=0.275$

$D2_f$ (UB_{12} type)

Cubic: O_h^5-Fm3m; $a=7.47$; $A=52$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$;)))+4U(O_h): 000
+48B(C_{2v}): $\pm(\frac{1}{2}xx;$); $\pm(\frac{1}{2}x\bar{x};$); $x=\frac{1}{8}$

$D2_g$ (Fe_8N type)

Tetragonal: $D_{4h}^{17}-I4/mmm$; $a=5.72$, $c=6.29$; $A=18$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$)+2N($D_{4h}$): 000
+4Fe(D_{2d}): $\frac{1}{2}0\frac{1}{4}$; $0\frac{1}{2}\frac{1}{4}$
+4Fe(C_{2v}): $\pm(00z)$; $z=0.56$
+8Fe(C_{2v}): $\pm(xx0)$; $\pm(x\bar{x}0)$; $x=\frac{1}{4}$

$D5_2$ (La_2O_3 type)

Hexagonal: $D_{3d}^{3}-P\bar{3}m1$; $a=3.93$, $c=6.12$, $c/a=1.56$; $A=5$
Co-ordinates: 2La(C_{3v}): $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}\bar{z}$; $z\approx 0.23$
1O(D_{3d}): 000; 2O(C_{3v}): $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}\bar{z}$; $z\approx 0.63$

Apart from the different c/a-values and small differences in the z-values this type is similar to the $D5_{13}$ (Ni_2Al_3) type.

$D5_3$ (Mn_2O_3 type)

Cubic: T_h^7-Ia3; $a=9.41$; $A=80$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$)+8Mn($C_{3i}$): $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; $\frac{1}{4}\frac{3}{4}\frac{3}{4}$;) ;
+24Mn(C_2): $\pm(x0\frac{1}{4};$); $\pm(x\frac{1}{2}\frac{3}{4};$); $x=-0.030$
+48O(C_1): $\pm(xyz;$); $\pm(x, \bar{y}; \frac{1}{2}-z;$); $\pm(\frac{1}{2}+x, \bar{y}, z;$); $\pm(x, \frac{1}{2}+y, \bar{z};$); $x=0.39$; $y=0.15$; $z=0.38$

$D5_8$ (Sb_2S_3 type)

Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=11.20$, $b=11.28$, $c=3.83$; $A=20$
Co-ordinates: 4Sb(C_s): $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.33$; $y=0.03$
4Sb(C_s): the same with $x=-0.04$; $y=-0.15$
4S(C_s): the same with $x=0.88$; $y=0.05$
4S(C_s): the same with $x=-0.44$; $y=-0.13$
4S(C_s): the same with $x=0.19$; $y=0.21$

Table 6.2 STRUCTURAL DETAILS *continued*

For other substances:

	M *I*	M *II*	S *I*	S *II*	S *III*
U_2S_3, x	0.311	−0.008	0.878	−0.439	0.206
y	−0.014	−0.195	0.053	−0.129	0.230
Th_2S_3, x	0.314	−0.019	0.878	−0.439	0.206
y	−0.022	−0.200	0.053	−0.129	0.230

$D5_9$ (Zn_3P_2 type)

Tetragonal: $D_{4h}^{15}-P4/nmc$; $a=8.10$, $c=11.45$; $A=40$
Co-ordinates: $4P(C_{2v})$: $\pm(00z)$; $\pm(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}+z)$; $z=0.25$
$4P(C_{2v})$: $0\frac{1}{2}z$; $\frac{1}{2}0\bar{z}$; $0\frac{1}{2}(\frac{1}{2}+z)$; $\frac{1}{2}0(\frac{1}{2}-z)$; $z=0.24$
$8P(C_s)$: $\pm(xx0; \bar{x}x0; \frac{1}{2}+x, \frac{1}{2}+x, \frac{1}{2}, \frac{1}{2}-x, \frac{1}{2}+x, \frac{1}{2})$; $x=0.26$
$8Zn(C_s)$: $0xz$; $0\bar{x}z$; $x0\bar{z}$; $\bar{x}0\bar{z}$; $\frac{1}{2}(\frac{1}{2}+x)$ $(\frac{1}{2}-z)$; $\frac{1}{2}(\frac{1}{2}-x)$ $(\frac{1}{2}-z)$; $(\frac{1}{2}+x)\frac{1}{2}(\frac{1}{2}+z)$; $(\frac{1}{2}-x)$ $\frac{1}{2}(\frac{1}{2}+z)$; $x=0.22$; $z=0.10$
$8Zn(Cs)$: the same with $x=0.28$; $z=0.39$
$8Zn(C_s)$: the same with $x=0.26$; $z=0.65$

$D5_{10}$(Cr_3C_2 type)

Orthorhombic: $D_{2h}^{16}-Pbnm$; $a=11.46$ $b=5.52$, $c=2.85$; $A=20$
Co-ordinates: $4C(C_s)$: $\pm(xy\frac{1}{4})$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{4})$; $x=0.11$; $y=-0.10$
$4C(C_s)$: the same with $x=-0.06$; $y=0.22$
$4Cr(C_s)$: the same with $x=4.406$; $y=0.03$
$4Cr(C_s)$: the same with $x=-0.230$; $y=0.175$
$4Cr(C_s)$: the same with $x=-0.070$; $y=-0.150$

$D5_{13}$ (Ni_2Al_3 type)

Hexagonal: $D_{3d}^{3}-C\bar{3}m$; $a=4.03$, $c=4.89$, $c/a=1.21$; $A=5$
Co-ordinates: $2Ni(C_{3v})$: $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}z$; $z=0.149$
$1Al(D_{3d})$: 000; $2Al(C_{3v})$: $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}z$; $z=0.648$

Apart from the different c/a-values and small differences in the z-values, this type is similar to the $D5_2$ (La_2O_3) type.

For Ni_2Ga_3: $z(Ni)=0.138$; $z(Ga)=0.625$
For Ni_2In_3: $z(Ni)=0.135$; $z(In)=0.641$

$D5_a$ (U_3Si_2 type)

Tetragonal: $D_{4h}^{5}-P4/mbm$; $a=7.33$, $c=3.90$; $A=10$
Co-ordinates: $2U(C_{4h})$: 000; $\frac{1}{2}\frac{1}{2}0$
$4U(C_{2v})$: $\pm(x, \frac{1}{2}+x, \frac{1}{2})$; $\pm(\frac{1}{2}+x, \bar{x}, \frac{1}{2})$; $x=0.181$
$4Si(C_{2v})$: $\pm(x, \frac{1}{2}+x, 0)$; $\pm(\frac{1}{2}+x, \bar{x}, \frac{1}{2})$; $x=0.389$

$D5_b$ (Pt_2Sn_3 type)

Hexagonal: $D_{6h}^{4}-P6/mmc$; $a=4.34$, $c=12.96$; $A=10$
Co-ordinates: $4Pt(C_{3v})$: $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{1}{3}, \frac{2}{3}, \frac{1}{2}-z)$; $z=0.14$
$4Sn(C_{3v})$: the same with $z=-0.07$
$2Sn(D_{3h})$: $\pm(00\frac{1}{4})$

$D5_c$ (Pu_2C_3 type)

Cubic: $T_d^6-I\bar{4}3d$; $a=8.13$; $A=40$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2})+16Pu(C_3)$: xxx; $(x+\frac{1}{4})$ $(x+\frac{1}{4})$ $(x+\frac{1}{4})$; $(\frac{1}{2}+x, \frac{1}{2}-x, \bar{x})$; ⟩; $(\frac{3}{4}+x)$ $(\frac{1}{4}-x)$ $(\frac{3}{4}-x)$; ⟩; $x=0.050$
$+24C(C_2)$: $y0\frac{1}{4}$; ⟩; $(\frac{1}{2}-y)0\frac{3}{4}$; ⟩; $(\frac{3}{4}+y)0\frac{3}{4}$; ⟩; $(\frac{3}{4}-y)0\frac{1}{4}$; ⟩; $y=0.28$

Table 6.2 STRUCTURAL DETAILS—*continued*

$D5_e$ (Ni_3S_2 type)

Rhombohedral: D_3^7-R32; $a=4.08$; $\alpha=89°\ 25'$; $A=5$
Co-ordinates: $3Ni(C_2)$: $\frac{1}{2}x\bar{x}$;) ; $x=\frac{1}{4}$
$2S(C_3)$: $\pm(xxx)$; $x=\frac{1}{4}$

$D5_f$ (As_2S_3 type)

Monoclinic: $C_{2h}^2-P2_1/n$; $a=11.48$, $b=9.58$, $c=4.23$; $\beta=90°\ 27'$; $A=20$
Co-ordinates: $4As(C_1)$: $\pm(xyz)$; $\pm(\frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{2}-z)$
All the other atoms in the same position.

	As *I*	As *II*	S *I*	S *II*	S *III*
x	0.268	0.482	0.410	0.340	0.125
y	0.187	0.313	0.120	0.380	0.305
z	0.161	−0.339	0.454	−0.046	0.455

$D7_1$ (Al_4C_3 type)

Rhombohedral: $D_{3d}^5-R\bar{3}m$; $a=8.53$; $\alpha=22°\ 28'$; $A=7$
(Hexagonal setting: $a=3.32$, $c=24.95$; $A=21$)
Co-ordinates: $1C(D_{3d})$: 000
$2C(C_{3v})$: $\pm(xxx)$; $x=0.217$
$2Al(C_{3v})$: the same with $x=0.293$
$2Al(C_{3v})$: the same with $x=0.128$

$D7_2$ (Co_3S_4 type)

Cubic: O_h^7-Fd3m; $a=9.38$; $A=56$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0;$) $+8Co(T_d)$: $000; \frac{1}{4}\frac{1}{4}\frac{1}{4}$
$+16Co(D_{3d})$: $\frac{5}{8}\frac{5}{8}\frac{5}{8}; \frac{7}{8}\frac{7}{8}\frac{7}{8};$)
$+32S(C_{3v})$: $xxx; x\bar{x}\bar{x};$) ; $(\frac{1}{4}-x)(\frac{1}{4}-x)(\frac{1}{4}-x)$; $(\frac{1}{4}-x)(\frac{1}{4}-x)(\frac{1}{4}+x)$;
); $x=-0.135$

An ordered variety of this type is described as $H1$ (Spinel) type.

$D7_3$ (Th_3P_4 type)

Cubic: $T_d^6-I\bar{4}3d$; $a=8.60$; $A=28$ (or less: ≈ 26)
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2})+12Th(S_4)$: $\frac{1}{4}\frac{3}{8}0;$) ; $\frac{3}{4}\frac{1}{8}0;$)
$+16P(C_3)$: xxx; $(\frac{1}{4}+x)(\frac{1}{4}+x)(\frac{1}{4}+x)$; $(\frac{1}{2}+x)(\frac{1}{2}+x)\bar{x}$;); $(\frac{3}{4}+x)(\frac{1}{4}-x)$
$(\frac{3}{4}-x)$;) ; $x=\approx\frac{1}{12}=0.083$

In the compounds (La, Ce, Ac, Pu, Am)$_2S_3$, $10\frac{2}{3}$ metal ions occupy the Th positions at random.

$D7_a$ (Ni_3Sn_4 type)

Monoclinic: C_{2h}^3-C2/m; $a=12.2$, $b=4.08$, $c=5.22$; $\beta=105°$; $A=14$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0)+2Ni(C_{2h})$: 000
$+4Ni(C_s)$: $\pm(x0z)$; $x=0.220$; $z=0.350$
$+4Sn(C_s)$: the same with $x=0.428$; $z=0.675$
$+4Sn(C_s)$: the same with $x=0.180$; $z=0.800$

$D7_b$ (Ta_3B_4 type)

Orthorhombic: $D_{2h}^{25}-Immm$; $a=3.29$, $b=14.00$, $c=3.13$; $A=14$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2})+2Ta(D_{2h})$; $000\frac{1}{2}$
$+4Ta(C_{2v})$: $\pm(0y0)$; $y=0.180$
$+4B(C_{2v})$: the same with $y=0.375$
$+4B(C_{2v})$: $\pm(0y\frac{1}{2})$; $y=0.444$

Table 6.2 STRUCTURAL DETAILS—*continued*

$D8_1$ (Fe_3Zn_{10} type)

Cubic: $O_h^9 - Im3m$; $a = 8.98$; $A = 52$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 12Fe($C_{4v}$): $\pm(x00;\ \text{◗})$; $x \approx \frac{1}{3}$
+ 16Zn(C_{3v}): $\pm(xxx;\ x\bar{x}\bar{x};\ \text{◗})$; $x \approx \frac{1}{6}$
+ 24Zn(C_{2v}): $\pm(xx0;\ \text{◗};\ x\bar{x}0;\ \text{◗})$; $x \approx \frac{1}{3}$

$D8_2$ (Cu_5Zn_8 type)

Cubic: $T_d^3 - I\bar{4}3m$; $a = 8.84$; $A = 52$
Co-ordinates: (000, $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 12Cu($C_{2v}$): $\pm(x00;\ \text{◗})$; $x = 0.355 \approx \frac{1}{3}$
+ 8Cu(C_{3v}): $xxx;\ x\bar{x}\bar{x};\ \text{◗}$; $x = -0.172 \approx -\frac{1}{6}$
+ 8Zn(C_{3v}): the same with $x = 0.110 \approx +\frac{1}{6}$
+ 24Zn(C_s): $xxz;\ \text{◗}$; $x\bar{x}\bar{z};\ \text{◗}$; $\bar{x}\bar{x}z;\ \text{◗}$; $\bar{x}x\bar{z};\ \text{◗}$; $x = 0.313 \approx \frac{1}{3}$;
$z = 0.036 \approx 0$

$D8_3$ (Cu_9Al_4 type)

Cubic: $T_d^1 - P\bar{4}3m$; $a = 8.69$; $A = 52$
Co-ordinates: 6Cu(C_{2v}): $\pm(x00;\ \text{◗})$; $x = 0.356 \approx \frac{1}{3}$
6Cu(C_{2v}): $+(x\frac{1}{2}\frac{1}{2};\ \text{◗})$; $x = 0.856 \approx \frac{1}{2} + \frac{1}{3}$
4Cu(C_{3v}): $xxx;\ x\bar{x}\bar{x};\ \text{◗}$; $x = -0.172 \approx -\frac{1}{6}$
4Cu(C_{3v}): the same with $x = 0.331 \approx \frac{1}{2} - \frac{1}{6}$
4Cu(C_{3v}): the same with $x = 0.601 \approx \frac{1}{2} + \frac{1}{6}$
4Al(C_{3v}): the same with $x = 0.112 \approx \frac{1}{6}$
12Al(C_s): $xxz;\ \text{◗};\ x\bar{x}\bar{z};\ \text{◗};\ \bar{x}\bar{x}z;\ \text{◗};\ \bar{x}x\bar{z}$; $x = 0.812 \approx \frac{1}{2} + \frac{1}{3}$; $z = 0.536 \approx \frac{1}{2}$
12Cu(C_s): the same with $x = 0.312 \approx \frac{1}{3}$; $z = 0.036 \approx 0$

$D8_4$ ($Cr_{23}C_6$ type)

Cubic: $O_h^5 - Fm3m$; $a = 10.64$; $A = 116$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$; ◗) + 4Cr(O_h): 000
+ 8Cr(T_d): $\pm(\frac{1}{4}\frac{1}{4}\frac{1}{4})$
+ 32Cr(C_{3v}): $\pm(xxx;\ x\bar{x}\bar{x};\ \text{◗})$; $x = 0.385$
+ 48Cr(C_{2v}): $\pm(xx0;\ \text{◗};\ x\bar{x}0;\ \text{◗})$; $x = 0.165$
+ 24C(C_{4v}): $\pm(x00;\ \text{◗})$; $x = 0.275$

$D8_5$ (Fe_7W_6 type)

Rhombohedral: $D_{3d}^5 - R\bar{3}m$; $a = 9.02$; $\alpha = 30°\ 31'$; $A = 13$
(Hexagonal setting: $a = 4.74$, $c = 25.75$; $A = 39$)
Co-ordinates: 1Fe(D_{3d}): 000
6Fe(C_s): $\pm(xxz;\ \text{◗})$; $x = 0.09$; $z = 0.59$
2W(C_{3v}): $\pm(xxx)$; $x = \frac{1}{6} = 0.167$
2W(C_{3v}): the same with $x = 0.346$
2W(C_{3v}): the same with $x = 0.448$

$D8_6$ ($Cu_{15}Si_4$ type)

Cubic: $T_d^6 - I\bar{4}3d$; $a = 9.69$; $A = 76$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 12Cu($S_4$): $0\frac{1}{4}\frac{3}{8}$; ◗; $0\frac{3}{4}\frac{1}{8}$; ◗;
+ 48Cu(C_1): $xyz;\ \text{◗};\ x\bar{y}(\frac{1}{2}-z);\ \text{◗};\ (\frac{1}{2}-x)y\bar{z};\ \text{◗};\ \bar{x}(\frac{1}{2}-y)z;\ \text{◗};\ (\frac{1}{4}+y)(\frac{1}{4}+x)(\frac{1}{4}+z);\ \text{◗};\ (\frac{1}{4}-y)(\frac{1}{4}+x)(\frac{3}{4}-z);\ \text{◗};\ (\frac{1}{4}+y)(\frac{3}{4}-x)(\frac{1}{4}-z);\ \text{◗};\ (\frac{3}{4}-y)(\frac{1}{4}-x)(\frac{1}{4}+z);\ \text{◗}$;
$x = 0.12$; $y = 0.16$; $z = 0.04$
+ 16Si(C_3): $xxx;\ x\bar{x}(\frac{1}{2}-x);\ \text{◗};\ (\frac{1}{4}+x)(\frac{1}{4}+x)(\frac{1}{4}+x);\ (\frac{1}{4}-x)(\frac{1}{4}+x)(\frac{3}{4}-x);\ \text{◗}$; $x = 0.208$

Table 6.2 STRUCTURAL DETAILS—*continued*

$D8_8$ (Mn_5Si_3 type)

Hexagonal: $D_{6h}^3 - P6_3/mcm$; $a=6.90$, $c=4.80$; $A=16$
Co-ordinates: $4Mn(D_3)$: $\frac{1}{3}\frac{2}{3}0$; $\frac{2}{3}\frac{1}{3}0$; $\frac{1}{3}\frac{2}{3}\frac{1}{2}$; $\frac{2}{3}\frac{1}{3}\frac{1}{2}$
$6Mn(C_{2v})$: $\pm(x0\frac{1}{4}; 0x\frac{1}{4}; \bar{x}\bar{x}\frac{1}{4})$; $x=0.23$
$6Si(C_{2v})$: the same with $x=0.60$
For Mg_5Hg_3: $x(Mg)=0.25$; $x(Hg)=0.615$

$D8_9$ (Co_9S_8 type)

Cubic: $O_h^5 - Fm3m$; $a=9.91$; $A=68$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0; \text{ }) + 4Co(O_h)$: $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
$+32Co(C_{3v})$: $\pm(xxx; x\bar{x}\bar{x}; \text{ })$; $x\approx\frac{1}{8}$
$+8S(T_d)$: $\pm(\frac{1}{4}\frac{1}{4}\frac{1}{4})$
$+24S(C_{4v})$: $\pm(x00; \text{ })$; $x\approx\frac{1}{4}$

$D8_{10}$ (Cr_5Al_8 type)

Rhombohedral: $C_{3v}^5 - R3m$; $a=7.79$; $\alpha=109°\ 8'$; $A=26$
(Hexagonal setting: $a=12.70$, $c=7.90$; $A=78$)
Co-ordinates: $1Cr(C_{3v})$: xxx; $x=0.097$
$3Cr(C_s)$: xxz; ; $x=-0.103$; $z=0.106$
$3Cr(C_s)$: the same with $x=0.170$; $z=-0.172$
$3Cr(C_s)$: the same with $x=0.003$; $z=0.352$
$1Al(C_{3v})$: xxx; $x=-0.164$
$3Al(C_s)$: xxz; ; $x=0.006$; $z=-0.352$
$3Al(C_s)$: the same with $x=0.291$; $z=0.058$
$3Al(C_3)$: the same with $x=-0.322$; $z=0.044$
$6Al(C_1)$: xyz; ; xzy; ; $x=0.330$; $y=-0.297$; $z=-0.042$

$D8_{11}$ (Co_2Al_5 type)

Hexagonal: $D_{6h}^4 - P6_3/mmc$; $a=7.66$, $c=7.59$; $A=28$
Co-ordinates: $2Co(D_{3h})$: $\frac{2}{3}\frac{1}{3}\frac{1}{4}$; $\frac{1}{3}\frac{2}{3}\frac{3}{4}$
$6Co(C_{2v})$: $\pm(x, 2x, \frac{1}{4}; 2\bar{x}, \bar{x}, \frac{1}{4}; x\bar{x}\frac{1}{4})$; $x=0.128$
$2Al(D_{3d})$: $000; 00\frac{1}{2}$
$6Al(C_{2v})$: $\pm(x, 2x, \frac{1}{4}; 2\bar{x}, \bar{x}, \frac{1}{4}; x\bar{x}\frac{1}{4})$; $x=0.467$
$12Al(C_s)$: $\pm(2x, x, z; \bar{x}, 2\bar{x}, z; \bar{x}xz; 2\bar{x}, \bar{x}, \frac{1}{2}+z; x, 2x, \frac{1}{2}+z; x, \bar{x}, \frac{1}{2}+z)$; $x=0.196$; $z=0.061$

$D8_a$ (Th_6Mn_{23} type)

Cubic: $O_h^5 - Fm3m$; $a=12.52$; $A=116$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0; \text{ }) + 24Th(C_{4v})$: $\pm(x00; \text{ })$; $x=0.207$
$+4Mn(O_h)$: $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
$+24Mn(D_{2h})$: $\frac{1}{4}\frac{1}{4}0$; ; $\frac{1}{4}\frac{3}{4}0$;
$+32Mn(C_{3v})$: $\pm(xxx; x\bar{x}\bar{x}; \text{ })$; $x=0.378$
$+32Mn(C_{3v})$: the same with $x=0.178$

$D8_b$ (σ type, as for example: V_3Ni_2)

(a) According to Bergman and Shoemaker[202]:
Tetragonal: $D_{4h}^{14} - P4/mnm$; for σ-FeCr: $a=8.80$, $c=4.55$; $A=30$
Co-ordinates: 2 atoms $A(D_{2h})$: $000; \frac{1}{2}\frac{1}{2}\frac{1}{2}$
4 atoms $B(C_{2v})$: $\pm(xx0)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-x, \frac{1}{2})$; $x=\frac{2}{5}=0.400$
8 atoms $C(C_s)$: $\pm(xy0)$; $\pm(yx0)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2})$; $\pm(\frac{1}{2}+y, \frac{1}{2}-x, \frac{1}{2})$; $x=\frac{7}{15}=0.468$; $y=\frac{2}{15}=0.134$
8 atoms $D(C_s)$: the same with $x=\frac{14}{15}=0.735$; $y=\frac{1}{15}=0.067$
8 atoms $E(C_s)$: $\pm(xxz)$; $\pm(xx\bar{z})$; $\pm(\frac{1}{2}+x, \frac{1}{2}-x, \frac{1}{2}+z)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-x, \frac{1}{2}-z)$; $x=\frac{11}{60}=0.183$; $z=\frac{1}{4}=0.250$

Table 6.2 STRUCTURAL DETAILS *continued*

The space groups $C_v^4 - P4nm$ and $D_{2d}^8 - P\bar{4}n2$ could not be ruled out.

(b) According to Kasper, Decker and Belanger,[203] who investigated σ-CoCr: the same space group; $a = 8.75$, $c = 4.54$; $A = 30$.
Co-ordinates: 2 atoms $A(D_{2h})$: $00\frac{1}{2}$; $\frac{1}{2}\frac{1}{2}0$
4 atoms B as under (a) but $x = 0.100$
8 atoms C as under (a) but $x = 0.373$; $y = 0.027$
8 atoms D as under (a) but $x = 0.573$; $y = 0.227$
8 atoms E as under (a) but $x = 0.300$; $z = \frac{1}{4}$

(c) Pearson and Christian,[204] who investigated σ-NiV, found best agreement between observed and calculated intensities when those atomic positions were used which were proposed by Tucker[115] for β-uranium [description as A_b (β-U type) on page 6-38]; Tetragonal: C_{4v}^4–$P4nm$; for σ-NiV: $a = 8.97$, $c = 4.64$; $A = 30$. An ordered arrangement is proposed with Ni taking the positions in which $z \approx 0$ or $\frac{1}{4}$ and with V taking the positions in which $z \approx \frac{1}{2}$ or $\frac{3}{4}$.

$D8_c$ ($Mg_2Cu_6Al_5$ type)

Cubic: $T_h^1 - Pm3$; $a = 8.31$; $A = 39$
Co-ordinates: 6Mg(C_{2v}): $\pm(x0\frac{1}{2};\)$; $x = 0.32$
6Cu(or Zn I)(C_{2v}): $\pm(x00;\)$; $x = 0.225$
12Cu(or Zn II)(C_s): $\pm(\frac{1}{2}yz;\)$; $\pm(\frac{1}{2}y\bar{z};\)$; $y = 0.243$; $z = 0.336$
1Al(or Zn III)(T_h): $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
6Al(or Zn IV)(C_{2v}): $\pm(x\frac{1}{2}0;\)$; $x = 0.16$
8Al(or Zn V)(C_3): $\pm(xxx;\ x\bar{x}\bar{x};\)$; $x = 0.215$
For Mg_2Zn_{11}: x(Zn I) = 0.235; y(Zn II) = 0.243; z(Zn II) = 0.343; x(Zn IV) = 0.160; x(Zn V) = 0.222.

$D8_d$ (Co_2Al_9)

Monoclinic: $C_{2h}^5 - P2_1/a = 8.56$, $b = 6.29$, $c = 6.21$; $\beta = 94°\ 46'$; $A = 22$
Co-ordinates: 2Al I(C_i) = 000; $0\frac{1}{2}\frac{1}{2}$
4 times Al, II, Al III, Al IV, Al V and Co in: $\pm(yyz)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-y, z)$

	Co	Al *II*	Al *III*	Al *IV*	Al *V*
x	0.3335	0.2682	0.2309	0.9986	0.0417
y	0.6149	0.9619	0.2899	0.1931	0.6148
z	0.2646	0.4044	0.0889	0.3891	0.2159

$D8_e$ ($Mg_{32}X_{49}$ type)

Cubic: $T_h^5 - Im3$; $a = 14.16$; $A = 162$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 12MG($C_{2v}$): $\pm(x0\frac{1}{2};\)$; $x = 0.605$
+ 12Mg(C_{2v}): ± the same with $x = 0.185$
+ 16Mg(C_3): $\pm(xxx;\ x\bar{x}\bar{x};\)$; $x = 0.185$
+ 24Mg(C_s): $\pm(0yz;\ ;\ 0y\bar{z};\)$; $y = 0.300$; $z = 0.115$
+ 2Al(T_h): 000
+ 24 atoms (83% Zn; 17% Al)(C_s): $\pm(0yz;\ ;\ 0y\bar{z};\)$; $y = 0.097$; $z = 0.157$
+ 24 atoms (44% Zn; 56% Al)(C_s): the same with $y = 0.195$; $z = 0.310$
+ 48 atoms (48% Zn; 52% Al)(C_s): $\pm(xyz;\ ;\ x\bar{y}\bar{z};\ ;\ \bar{x}y\bar{z};\ ;\ \bar{x}\bar{y}z;\)$; $x = 0.160$; $y = 0.190$; $z = 0.400$

$D8_f$ (Ir_3Sn_7 type)

Cubic: $O_h^9 - Im3m$; $a = 9.36$; $A = 40$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 12Tr($C_{4v}$): $\pm(x00;\)$; $x = 0.342$
+ 12Sn(D_{2d}): $\pm(\frac{1}{4}0\frac{1}{2}),\)$
+ 16Sn(C_{3v}): $(xxx;\ x\bar{x}\bar{x};\)$; $x = 0.156$

Table 6.2 STRUCTURAL DETAILS—*continued*

$D8_g$ (Mg_5Ga_2 type)

Orthorhombic: $D_{2h}^{26}-Ibam$; $a=13.72$, $b=7.00$, $c=6.02$; $A=28$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2})+8Ga(C_s)$: $\pm(xy0)$; $\pm(x\bar{y}\frac{1}{2})$; $x=0.122$; $y=0.262$
$+8Mg(C_s)$: the same with $x=0.080$; $y=0.660$
$+8Mg(C_2)$: $\pm(x0\frac{1}{4})$; $\pm(\bar{x}0\frac{1}{4})$; $x=0.242$
$+4Mg(D_2)$: $\pm(00\frac{1}{4})$

[Unpublished work by E. Hellner; for Mg_5Tl_2: $x(Tl)\approx\frac{1}{8}$; $y(Tl)\approx\frac{1}{4}$]

$D8_h$ (W_2B_5 type)

Hexagonal: $D_{6h}^4-P6_3/mmc$; $a=2.98$, $c=13.87$; $A=14$
Co-ordinates: $4W(C_{3v})$: $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{1}{3}, \frac{2}{3}, \frac{1}{2}-z)$; $z=0.139$
$2B(D_{3h})$: $\pm(00\frac{1}{4})$; $+2B(D_{3h})$: $\pm(\frac{1}{3}\frac{2}{3}\frac{3}{4})$
$2B(D_{3d})$: 000; $00\frac{1}{2}$
$4B(C_{3v})$: $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{1}{3}, \frac{2}{3}, \frac{1}{2}-z)$; $z=-0.028$

$D8_i$ (Mo_2B_5 type)

Rhombohedral: $D_{3d}^5-R\bar{3}m$; $a=7.19$; $\alpha=24°\ 10'$; $A=7$
(Hexagonal setting: $a=3.01$, $c=20.93$; $A=21$)
Co-ordinates (for hex. setting): $(000; \frac{1}{3}\frac{2}{3}\frac{1}{3}; \frac{2}{3}\frac{1}{3}\frac{2}{3})+6Mo(C_{3v})$: $\pm(00z)$; $z=0.075$
$+6B(C_{3v})$: the same with $z=\frac{1}{3}$
$+6B(C_{3v})$: the same with $z=0.186$
$+3B(D_{3d})$: $00\frac{1}{2}$

$D8_k$ (Th_7S_{12} type)

Hexagonal: $C_{6h}^2-P6_3/m$; $a=11.04$, $c=3.98$; $A=19$
Co-ordinates: $1Th(S_6)$: $\pm(00\frac{1}{4})$
$6Th(C_s)$: $\pm(xy\frac{1}{4})$; $\pm(\bar{y}, x-y, \frac{1}{4})$; $\pm(y-x, \bar{x}, \frac{1}{4})$; $x=0.153$; $y=-0.283$
$6S(C_s)$: the same with $x=0.514$; $y=0.375$
$6S(C_s)$: the same with $x=0.235$; $y=0\pm0.010$

$E0_7$ (FeAsS type)

Monoclinic: $C_{2h}^5-B2_1/d$; $a=9.51$, $b=5.65$, $c=6.42$; $\beta\approx90°$; $A=24$
Co-ordinates: $(000; \frac{1}{2}0\frac{1}{2})+8Fe(C_1)$: $\pm(xyz)$; $\pm(\frac{3}{4}+x, \frac{1}{2}-y, \frac{3}{4}+z)$; $x=0$; $y=0$; $z=0.275$
$+8As(C_1)$: the same with $x=0.147$; $y=0.128$; $z=0$
$+8S(C_1)$: the same with $x=0.167$; $y=0.132$; $z=0.500$

$E1_1$ ($CuFeS_2$ type)

Tetragonal: $D_{2d}^{12}-I\bar{4}2d$; $a=5.24$, $c=10.30$; $A=16$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}\frac{1}{2})+4Cu(S_4)$: 000; $\frac{1}{2}0\frac{1}{4}$
$+4Fe(S_4)$: $00\frac{1}{2}$; $\frac{1}{2}0\frac{3}{4}$
$+8S(C_2)$: $\frac{1}{4}y\frac{1}{8}$; $\frac{3}{4}\bar{y}\frac{1}{8}$; $y\frac{37}{48}$; $\bar{y}\frac{17}{48}$; $y=0.27$

$E1_a$ ($MgCuAl_2$ type)

Orthorhombic: $D_{2h}^{17}-Cmcm$; $a=4.00$, $b=9.28$, $c=7.14$; $A=16$
Co-ordinates: $(000; \frac{1}{2}\frac{1}{2}0)+4Mg(C_{2v})$: $\pm(0y\frac{1}{4})$; $y=0.072$
$+4Cu(C_{2v})$: $\pm(0y\frac{1}{4})$; $y=-0.222$
$+8Al(C_s)$: $\pm(0yz)$; $\pm(0, y, \frac{1}{2}-z)$; $y=0.356$; $z=0.056$

Table 6.2 STRUCTURAL DETAILS—*continued*

$E1_b$ [AuAgTe$_4$ (Sylvanite) type]

Monoclinic: $C_{2h}^4 - P2/c$; $a = 8.96$, $b = 4.49$, $c = 14.62$; $\beta = 145°\ 26'$; $A = 12$
Co-ordinates: 2Au(C_i): 000; $00\frac{1}{2}$
2Ag(C_2): $\pm(0y\frac{1}{4})$; $y = 0.433$
4Te(C_1): $\pm(xyz)$; $\pm(x, \bar{y}, \frac{1}{2}+z)$; $x = 0.298$; $y = 0.031$; $z = 0.999$
4Te(C_1): the same with $x = 0.277$; $y = 0.425$; $z = 0.235$

$E9_3$ (Fe_3W_3C type)

Cubic: $O_h^7 - Fd3m$; $a = 11.04$; $A = 112$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$;) + 16Fe(D_{3d}): $\frac{5}{8}\frac{5}{8}\frac{5}{8}$; $\frac{5}{8}\frac{7}{8}\frac{7}{8}$;)
+ 32Fe(C_{3v}): xxx; $x\bar{x}\bar{x}$;); $(\frac{1}{4}-x)(\frac{1}{4}-x)(\frac{1}{4}-x)$; $(\frac{1}{4}-x)(\frac{1}{4}+x)(\frac{1}{4}+x)$;); $x = 0.175$
+ 48W(C_{2v}): $\pm(x00;$); $(\frac{1}{4}+x)\frac{1}{4}\frac{1}{4}$;); $(\frac{1}{4}-x)\frac{1}{4}\frac{1}{4}$; $x = 0.195$
+ 16C(C_{3d}): $\frac{1}{8}\frac{1}{8}\frac{1}{8}$; $\frac{3}{8}\frac{3}{8}\frac{3}{8}$;)

$E9_4$ (Al_3C_3N type)

Hexagonal: $C_{6v}^4 - P6_3mc_3$; $a = 3.28$, $c = 21.55$; $A = 18$
Co-ordinates: 2Al(C_{3v}): $00z$; $00(\frac{1}{2}+z)$; $z = 0.150$
2Al(C_{3v}): the same with $z = 0.345$
2Al(C_{3v}): $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}(\frac{1}{2}+z)$; $z = 0.045$
2Al(C_{3v}): the same with $z = 0.456$
2Al(C_{3v}): the same with $z = 0.240$
2C(C_{3v}) the same with $z = 0.133$
2C(C_{3v}): the same with $z = 0.369$
2C(C_{3v}): $00z$; $00(\frac{1}{2}+z)$; $z = 0.001$
2N(C_{3v}): the same with $z = 0.250$

$E9_a$ ($FeCu_2Al_7$ type)

Tetragonal: $D_{4h}^6 - P4mnc$; $a = 6.32$, $c = 14.78$; $A = 40$
Co-ordinates: 4Fe(C_4): $\pm(00z)$; $\pm(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}+z)$; $z = 0.300$
8Cu(C_s): $\pm(xy0)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2})$; $\pm(\bar{y}x0)$; $\pm(\frac{1}{2}+y, \frac{1}{2}+x, \frac{1}{2})$; $x = 0.278$; $y = 0.092$
4Al(C_4): $\pm(00z)$; $\pm(\frac{1}{2}, \frac{1}{2}, \frac{1}{2}+z)$; $z = 0.122$
8Al(C_2): $\pm(x, \frac{1}{2}+x, \frac{1}{4}; \bar{x}, \frac{1}{2}-x, \frac{1}{4}; \frac{1}{2}-x, x, \frac{1}{4})$; $x = 0.167$
16Al(C_1): $\pm(xyz; \bar{x}\bar{y}z; \bar{y}xz; y\bar{x}z; \frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2}+z; \frac{1}{2}-x, \frac{1}{2}+y, \frac{1}{2}+z;$
$\frac{1}{2}+y, \frac{1}{2}+x, \frac{1}{2}+z; \frac{1}{2}-y, \frac{1}{2}-x, \frac{1}{2}+z)$; $x = 0.203$; $y = 0.414$; $z = 0.100$

$E9_b$ ($FeMg_3Al_8Si_6$ type)

Hexagonal $D_{3h}^3 - P\bar{6}2m$; $a = 6.62$, $c = 7.92$; $A = 18$
Co-ordinates: 1Fe(D_{3h}): 000
3Mg(C_{2v}): $x0\frac{1}{2}$; $0x\frac{1}{2}$; $\bar{x}\bar{x}\frac{1}{2}$; $x = 0.445$
1Al(D_{3h}): $00\frac{1}{2}$
3Al(C_{2v}): $x00$; $0x0$; $\bar{x}\bar{x}0$; $x = 0.403$
4Al(C_3): $\pm(\frac{1}{3}\frac{2}{3}z)$; $\pm(\frac{2}{3}\frac{1}{3}\bar{z})$; $z = 0.231$
6Si(C_s): $x0z$; $x0\bar{z}$; $0xz$; $0x\bar{z}$; $\bar{x}\bar{x}z$; $\bar{x}\bar{x}\bar{z}$; $x = 0.750$; $z = 0.223$

$E9_c$ (Mn_3Al_9Si type)

Hexagonal: $D_{4h}^6 - P6_3/mmc$; $a = 7.51$, $c = 7.74$; $A = 26$
Co-ordinates: 6Mn(C_{2v}): $\pm(x, 2x, \frac{1}{4})$; $\pm(2x, x, \frac{3}{4})$; $\pm(x\bar{x}\frac{1}{4})$; $x = 0.120$
6Al(C_{2v}): the same with $x = 0.458$
12Al(C_s): $\pm(x, 2x, z; 2x, x, \bar{z}; x\bar{x}z; x, 2x, \frac{1}{2}-z; 2x, x, \frac{1}{2}+z; x, \bar{x}, \frac{1}{2}-z)$; $x = 0.201$;
$z = -0.067$
2Si(D_{3d}): 000; $00\frac{1}{2}$

Table 6.2 STRUCTURAL DETAILS—*continued*

$E9_d$ ($AlLi_3N_2$ type)

Cubic: $T_h^7 - Ia3$; $a = 9.48$; $A = 96$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + 16Al($C_3$): $\pm(xxx)$; $\pm(\frac{1}{2}+x, \frac{1}{2}-x, \bar{x};$ ↻); $x = 0.115$
+ 48Li(C_1): $\pm(xyz;$ ↻); $\pm(x, \bar{y}, \frac{1}{2}-z;$ ↻); $\pm(\frac{1}{2}-x, y, \bar{z};$ ↻); $\pm(\bar{x}, \frac{1}{2}-y, z;$ ↻); $x = 0.160$; $y = 0.382$; $z = 0.110$
+ 8N(C_{3i}): 000; $\frac{1}{2}\frac{1}{2}0$; ↻
+ 24N(C_2): $\pm(x0\frac{1}{4};$ ↻); $\pm(\bar{x}\frac{1}{2}\frac{1}{4};$ ↻); $x = 0.205$
For $GaLi_3N_2$: x(Ga) = 0.117; x(Li) = 0.152; y(Li) = 0.381; z(Li) = 0.114; x(N) = 0.215

$E9_e$ [$CuFe_2S_3$ (Cubanite) type]

Orthorhombic: $D_{2h}^{16} - Pnma$; $a = 6.23$, $b = 11.12$, $c = 6.46$; $A = 24$
Co-ordinates: 4Cu(C_s): $\pm(x\frac{1}{4}z)$; $\pm(\frac{1}{2}-x, \frac{3}{4}, \frac{1}{2}+z)$; $x = \frac{1}{8}$; $z = \frac{7}{12}$
8Fe(C_1): $\pm(xyz; \frac{1}{2}+x, \frac{1}{2}-y, \frac{1}{2}-z; \bar{x}, \frac{1}{2}+y, \bar{z}; \frac{1}{2}-x, \bar{y}, \frac{1}{2}+z)$; $x = \frac{1}{8}$; $y = \frac{1}{12}$; $z = \frac{1}{12}$
8S(C_1): the same with $x = \frac{1}{4}$; $y = \frac{1}{12}$; $z = \frac{5}{12}$
4S(C_s): $\pm(x\frac{1}{4}z)$; $\pm(\frac{1}{2}-x, \frac{3}{4}, \frac{1}{2}+z)$; $x = \frac{1}{4}$; $z = \frac{11}{12}$

$F0_1$ [NiSbS (Ullmannite) type]

Cubic: $T^4 - P2_13$; $a = 5.60$; $A = 12$
Co-ordinates: 4Ni(C_3): xxx; $(\frac{1}{2}+x)(\frac{1}{2}-x)\bar{x}$; ↻ ; $x \approx 0$
4Sb(C_3): the same with $x \approx 0.385$
4S(C_3): the same with $x \approx 0.615$

$F5_1$ ($NaHF_2$ type)

Rhombohedral: $D_{3d}^5 - R\bar{3}m$; $a = 5.05$; $\alpha = 40°\ 2'$; $A = 4$
(Hexagonal setting: $a = 3.45$, $c = 13.90$, $c/a = 4.03$; $A = 12$)
Co-ordinates: 1Na(D_{3d}): 000; 1H(D_{3d}) = $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
2F(C_{3v}): $\pm(xxx)$; $x = 0.410$
For $CaCN_2$: $\alpha = 43°\ 50'$; $c/a = 3.63$; $x = 0.37$
For $NaCrS_2$: $\alpha = 29°\ 48'$; $c/a = 5.59$; $x = 0.236$
For $NaCrSe_2$: $\alpha = 30°\ 18'$; $c/a = 5.49$; $x = 0.235$
For $RbCrSe_2$: $\alpha = 21°\ 33'$; $c/a = 7.85$

$F5_6$ ($CuSbS_2$ type)

Orthorhombic: $D_{2h}^{16} - Pnma$; $a = 6.01$, $b = 3.78$, $c = 14.46$; $A = 16$
Co-ordinates: 4Cu(C_s): $\pm(x\frac{1}{4}z)$; $\pm(\frac{1}{2}+x, \frac{1}{4}, \frac{1}{2}-z)$; $x = 0.25$; $z = 0.83$
4Sb(C_s): the same with $x = 0.23$; $z = 0.06$
4S(C_s): the same with $x = 0.63$; $z = 0.10$
4S(C_s): the same with $x = 0.88$; $z = 0.83$

$F5_a$ ($KFeS_2$ type)

Monoclinic: $C_{2h}^6 - C2/c$; $a = 7.05$, $b = 11.28$, $c = 5.40$; $\beta = 112°\ 30'$; $A = 16$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$) + 4K(C_2): $\pm(0y\frac{1}{4})$; $y = 0.355$
+ Fe(C_2): the same with $y = -0.008$
+ 8S(C_1): $\pm(xyz)$; $\pm(x, \bar{y}, \frac{1}{2}+z)$; $x = 0.195$; $y = 0.111$; $z = 0.10$

$H1_1$ [Spinel (Al_2MgO_4) type]

Cubic: $O_h^7 - Fd3m$; $a = 8.06$; $A = 56$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$; ↻) + 8Mg(I_d): 000; $\frac{1}{4}\frac{1}{4}\frac{1}{4}$
+ 16Al(D_{3d}): $\frac{5}{8}\frac{5}{8}\frac{5}{8}$; $\frac{2}{8}\frac{7}{8}\frac{7}{8}$; ↻
+ 32O(C_{3v}): xxx; $x\bar{x}\bar{x}$; ↻ ; $(\frac{1}{4}-x)(\frac{1}{4}-x)(\frac{1}{4}-x)$; $(\frac{1}{4}-x, \frac{1}{4}+x, \frac{1}{4}+x)$; ↻ ; $x \approx -\frac{1}{8}$

In some compounds, better agreement with observed intensities is obtained by assuming that the metal atoms are distributed at random among the 24 available sites, or that the trivalent element occupies all the 8-equivalent sites and half of the 16-equivalent ones. In some cases lattice sites may be vacant, e.g., γ-Al_2O_3 or In_2S_3.

Table 6.2 STRUCTURAL DETAILS—*continued*

$H2_4$[Cu_3VS_4 (Sulvanite) type]

Cubic: $T_d^1 - P\bar{4}3m$; $a = 5.37$; $A = 8$
Co-ordinates: $3Cu(D_{2d})$: $\frac{1}{2}00$; $0\frac{1}{2}0$; $00\frac{1}{2}$
$1V(T_d)$: 000
$4S(C_{3v})$: xxx; $x\bar{x}\bar{x}$; ⟩ ; $x = 0.235$

$H2_6$ [Stannite ($FeCu_2SnS_4$) type]

Tetragonal: $D_{2d}^{11} - I\bar{4}2m$; $a = 5.46$; $c = 10.72$; $A = 16$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + $2Fe(D_{2d})$: 000
+ $2Sn(D_{2d})$: $00\frac{1}{2}$
+ $4Cu(S_4)$: $0\frac{1}{2}\frac{1}{4}$; $\frac{1}{2}0\frac{1}{4}$
+ $8S(C_s)$: xxz; $\bar{x}\bar{x}z$; $x\bar{x}\bar{z}$; $\bar{x}x\bar{z}$; $x = 0.245$; $z = 0.132$

$L1_0$ (CuAu type)

Tetragonal: $D_{4h}^1 - C4/mmm$; $a = 3.98$m $c = 3.72$; $A = 4$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$) + $2Cu(D_{4h})$: 000
+ $2Au(D_{4h})$: $\frac{1}{2}0\frac{1}{2}$
Superstructure of the $A1$ (Cu) type

$L1$ (CuPt type)

Rhombohedral: $D_{3d}^5 - R\bar{3}m$; $a = 7.56$; $\alpha = 90°\ 54'$; $A = 32$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$; ⟩) + $16Cu(D_{3d})$: 000; $\frac{1}{4}\frac{1}{4}\frac{1}{2}$; ⟩
+ $16Pt(D_{3d})$: $\frac{1}{2}\frac{1}{2}\frac{1}{2}$; $\frac{3}{4}\frac{3}{4}0$ ⟩
Superstructure of $A1$ (Cu) type

$L1_2$ (Cu_3Au type)

Cubic: $O_h^1 - Pm3m$; $a = 3.75$; $A = 4$
Co-ordinates: $3Cu(D_{4h})$: $\frac{1}{2}\frac{1}{2}0$; ⟩
$1Au(O_h)$: 000
Superstructure of $A1$ (Cu) type

$L1_a$ (Pt_3Cu type)

Cubic: $O^3 - Fm3c$; $a \approx 5.6$; $A = 32$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$; ⟩) + $4Pt(O)$: 000
+ $4Cu(O)$: $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
+ $24(Pt, Cu)(D_2)$: $0\frac{1}{4}\frac{1}{4}$; ⟩ ; $\frac{1}{2}\frac{1}{4}\frac{1}{4}$; ⟩

This structure was suggested by Tang.[205] An alternative has been proposed by Schneider and Esch.[206]

$L2_1$ (Cu_2MnAl type)

Cubic: $O_h^5 - Fm3m$; $a = 5.90$; $A = 16$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}0$; ⟩ + $4Al(O_h)$: 000
+ $8Cu(I_d)$: $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; $\frac{3}{4}\frac{3}{4}\frac{3}{4}$
+ $4Mn(O_h)$: $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

Superstructure of the $A2$ (W) type; this type is virtually identical with the D_{o3} (BiF_3 or $BiLi_3$) type

$L2_2$ (Tl_7Sb_2 type)

Cubic: $O_h^9 - Im3m$; $a = 11.59$; $A = 54$
Co-ordinates: (000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$) + $2Tl(O_h)$: 000
+ $16Tl(C_{3v})$: $\pm(xxx, x\bar{x}\bar{x}$; ⟩); $x = 0.17 \approx \frac{1}{6}$
+ $24Tl(C_{2v})$: $\pm(xx0$; ⟩ ; $x\bar{x}0$; ⟩ ; $x = 0.35 \approx \frac{1}{3}$
+ $12Sb(C_{4v})$: $\pm(x00$; ⟩); $x = 0.29 \approx \frac{1}{3}$

Table 6.2 STRUCTURAL DETAILS—*continued*

$L2_a$ (δ-TiCu type)

Tetragonal: $D_{4h}^1 - P4/mmm$; $a = 3.14$, $c = 2.86$; $A = 2$
Co-ordinates: 1Ti(D_{4h}): 000
1Cu(D_{4h}): $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

L'_1 (Fe_4N type)

Cubic: $O_h^1 - Pm3m$ or $O_h^5 - Fm3m$ (depending on the distribution of the N atoms); $a = 3.79$; $A = 5$
Co-ordinates: 4Fe at 000; $\frac{1}{2}\frac{1}{2}0$;)
1N at $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; or at $\frac{1}{2}\frac{1}{2}\frac{1}{2}$, probably the latter; or at random at $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; $\frac{3}{4}\frac{3}{4}\frac{1}{4}$;) ; and (or) at $\frac{3}{4}\frac{3}{4}\frac{3}{4}$; $\frac{1}{4}\frac{1}{4}\frac{3}{4}$;) ; and (or) at $\frac{1}{2}\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}00$;)

$L'1_2$ ($\sim AlFe_3C$ type)

Cubic: $O_h^1 - Pm3m$; $a = 3.76$; $A \approx 5$
Co-ordinates: 1Al(O_h): 000
3Fe(D_{4h}): $\frac{1}{2}00$;)
0.6 to 0.9C(O_h) at $\frac{1}{2}\frac{1}{2}\frac{1}{2}$

$L'2$ (Martensite type)

Tetragonal: $D_{4h}^{17} - I4/mmm$; $a \approx 2.84$, $c = 2.97$; $A = 2Fe + (up\ to)\ 0.12\ C$
Co-ordinates: 2Fe(D_{4h}) at 000; $\frac{1}{2}\frac{1}{2}\frac{1}{2}$
The C atoms at random: $\frac{1}{2}\frac{1}{2}0$ and (or) $00\frac{1}{2}$

$L'3$ (Interstitial $A3$ type)

Hexagonal: $D_{6h}^4 - P6_3/mmc$ or $D_{6h}^1 - P6/mmm$
Co-ordinates: 2 metal atoms (D_{3h}): $\frac{2}{3}\frac{1}{3}0$; $\frac{1}{3}\frac{2}{3}\frac{1}{2}$
C or N(C_{3v}): $\frac{1}{3}\frac{2}{3}z$; $\frac{2}{3}\frac{1}{3}(\frac{1}{2}+z)$; $\frac{1}{3}\frac{2}{3}\bar{z}$; $\frac{2}{3}\frac{1}{3}(\frac{1}{2}-z)$; $z \approx \frac{3}{8}$; or $00\frac{1}{4}$; $00\frac{3}{4}$

$L6_0$ (Ti_3Cu type)

Tetragonal: $D_{4h}^1 - P4/mmm$; $a = 4.16$, $c = 3.59$; $A = 4$
Co-ordinates: 1Cu(D_{4h}): 000
1Ti(D_{4h}): $\frac{1}{2}\frac{1}{2}0$
2Ti(D_{2h}): $0\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}0\frac{1}{2}$

Tetragonal deformed $L1_2$ (Cu_3Au) type; superstructure of $A6$ (In) type

$L'6$ (Interstitial $A6$ type)

Tetragonal: $D_{4h}^{17} - F4/mmm$ (or $D_{4h}^1 - P4/mmm$, depending on the distribution of the N atoms)
Co-ordinates: 4 metal atoms (D_{4h}): 000; $\frac{1}{2}\frac{1}{2}0$;)
N atoms in the holes: $\frac{1}{4}\frac{1}{4}\frac{1}{4}$; $\frac{1}{4}\frac{3}{4}\frac{3}{4}$;) ; $\frac{3}{4}\frac{3}{4}\frac{3}{4}$; $\frac{3}{4}\frac{1}{4}\frac{1}{4}$;) ; or $\frac{1}{2}\frac{1}{2}\frac{1}{2}$; $\frac{1}{2}00$;)

Table 6.3 COMPARISON OF STRUKTURBERICHT AND PEARSON NOMENCLATURE

Strukturbericht structural type	*Typical compound or element*	*Pearson symbol*
A1	Cu	cF4
A2	W	cI2
A3	Mg	hP2
A4	C (Diamond)	cF8
A5	Sn (Beta)	tI4
A6	In	tI2
A7	As	hR2
A8	Gamma-Se	hP3
A9	C (Graphite)	hP4

Table 6.3 COMPARISON OF STRUKTURBERICHT AND PEARSON NOMENCLATURE—*continued*

Strukturbericht structural type	*Typical compound or element*	*Pearson symbol*
*A*10	Hg	hR1
*A*11	Ga	oC8
*A*12	Alpha-Mn	cI58
*A*13	Beta-Mn	cP20
*A*15	Cr_3Si	cP8
*A*16	Alpha-S	oF128
*A*20	Alpha-U	oC4
A_a	Pa	tI2
A_b	Beta-U	tP30
A_c	Alpha-Np	oP8
A_d	Beta-Np	tP4
A_e	Beta-$TiCu_3$	oF4
A_f	$HgSn_{10}$	hP1
A_g	B	tP50
A_h	Alpha-Po	cP1
A_i	Beta-Po	hR1
A_k	Alpha-Se	mP32
A_l	Beta-Se	mP32
*B*1	NaCl	cF8
*B*2	CsCl	cP2
*B*3	ZnS (Sphalerite)	cP2
*B*4	ZnS (Würtzite)	hP4
$B8_1$	NiAs	hP4
$B8_2$	Ni_2In	hP6
*B*9	HgS	hP6
*B*10	LiOH; PbO	tp4
*B*13	NiS	hR6
*B*16	GeS	oP8
*B*17	PtS	tP4
*B*18	CuS	hP12
*B*19	AuCd	oP4
*B*20	FeSi	cP8
*B*27	FeB	oP8
*B*29	SnS	oP8
*B*31	MnP	oP8
*B*32	NaTl	cF16
*B*34	PdS	tP16
*B*35	CoSn	hP6
*B*37	TlSe	tI16
B_a	UCo	cI16
B_b	AgZn	hP9
B_c	CaSi	oP16
B_d	NiSi	oP8
B_e	CdSb	oP16
B_f	CrB	oC8
B_g	MoB	tI16
B_h	WC	hP2
B_i	MoC	hP8
B_k	BN	hP4
B_l	AsS	mP32
B_m	TiB	oP8
*C*1	CaF_2	cF12
*C*2	FeS_2	cP12
*C*6	CdI_2	hP3
*C*7	MoS_2	hP6
$C11_a$	CaC_2	tI6
$C11_b$	$MoSi_2$	tI6
*C*12	$CaSi_2$	hR6
*C*14	$MgZn_2$	hP12
*C*15	$MgCu_2$	cF24
$C15_b$	$AuBe_5$	cF24
*C*16	$CuAl_2$	tI12
*C*18	FeS_2 (Marcasite)	oP6
*C*22	Fe_2P	hP9

Table 6.3 COMPARISON OF STRUKTURBERICHT AND PEARSON NOMENCLATURE—*continued*

Strukturbericht structural type	*Typical compound or element*	*Pearson symbol*
*C*23	$PbCl_2$	oP12
*C*32	AlB_2	hP3
*C*33	Bi_2Te_2S	hR5
*C*34	$AuTe_2$ (Calaverite)	mC6
*C*36	$MgNi_2$	hP24
*C*37	Co_2Si	oP12
*C*38	Cu_2Sb	tP6
*C*40	$CrSi_2$	hP9
*C*42	SiS_2	oI12
*C*44	GeS_2	oF72
*C*46	$AuTe_2$ (Krennerite)	oP24
*C*49	$ZrSi_2$	oC12
*C*54	$TiSi_2$	oF24
C_a	Mg_2Ni	hP18
C_b	Mg_2Cu	oF48
C_c	$ThSi_2$	tI12
C_e	$CoGe_2$	oC24
C_g	ThC_2	mC12
C_h	$CuTe_2$	hP6
C_h	$LiZn_2$	hP3
DO_2	$CoAs_3$	cI32
DO_3	BiF_3	cF16
DO_9	ReO_3/Cu_3N	cF4
DO_{11}	Fe_3C	oP16
DO_{18}	Na_3As	hP8
DO_{19}	Mg_3Cd	hP8
DO_{20}	$NiAl_3$	oP16
DO_{21}	Cu_3P	hP24
DO_{22}	$TiAl_3$	oP16
DO_{23}	$ZrAl_3$	tI16
DO_{24}	$TiNi_3$	hP16
DO_a	$TiCu_3$	oP8
DO_b	Ag_3Ga	hP9
DO_c	U_3Si	tI16
DO_d	Mn_3As	oP16
$D1_3$	$BaAl_4$	tI10
$D1_a$	$MoNi_4$	tI10
$D1_b$	UAl_4	oI20
$D1_c$	$PtSn_4$	oC20
$D1_d$	$PtPb_4$	tP10
$D1_e$	UB_4	tP20
$D1_f$	MnB_4	oF40
$D1_g$	B_4C	hR15
$D2_1$	CaB_6	cP7
$D2_3$	$NaZn_{13}$	cF112
$D2_a$	$TiBe_{12}$	hP13
$D2_b$	$ThMn_{12}$	tI26
$D2_c$	U_6Mn	tI26
$D2_d$	$CaCu_5$	hP6
$D2_e$	$BaHg_{11}$	cP36
$D2_f$	UBe_{12}	cF52
$D2_g$	Fe_8N	tI18
$D5_2$	La_2O_3	hP5
$D5_3$	Mn_2O_3	cI80
$D5_8$	Sb_2S_3	oP20
$D5_9$	Zn_3P_2	tP40
$D5_{10}$	Cr_3C_2	oP20
$D5_{13}$	Ni_2Al_3	hP5
$D5_a$	U_3Si_2	tP10
$D5_b$	Pt_2Sn_3	hP10
$D5_c$	Pu_2C_3	cI40
$D5_e$	Ni_3S_2	hR5
$D5_f$	As_2S_3	mP20
$D7_1$	Al_4C_3	hP7

Table 6.3 COMPARISON OF STRUKTURBERICHT AND PEARSON NOMENCLATURE—*continued*

Strukturbericht structural type	*Typical compound or element*	*Pearson symbol*
$D7_2$	Co_3S_4	cF56
$D7_3$	Th_3P_4	cI28
$D7_a$	Ni_3Sn_4	mC14
$D7_b$	Ta_3B_4	oI14
$D8_1$	Fe_3Zn_{10}	cI52
$D8_2$	Cu_5Zn_8	cI52
$D8_3$	Cu_9Al_4	cP52
$D8_4$	$Cr_{23}C_6$	cF116
$D8_5$	Fe_7W_6	hR13
$D8_6$	$Cu_{15}Si_4$	cI76
$D8_8$	Mn_5Si_3	hP16
$D8_9$	Co_9S_8	cF68
$D8_{10}$	Cr_5Al_8	hR26
$D8_{11}$	Co_2Al_5	hP28
$D8_a$	Th_6Mn_{23}	cF116
$D8_b$	Sigma (FeCr)	tP30
$D8_c$	$Mg_2Cu_6Al_5$ (Mg_2Zn_{11})	cP39
$D8_d$	Co_2Al_9	mP22
$D8_e$	$Mg_{32}X_{49}$ (X = Al, Zn)	cI162
$D8_f$	Ir_3Sn_7	cI40
$D8_g$	Mg_5Ga_2	oI28
$D8_h$	W_2B_5	hP14
$D8_i$	Mo_2B_5	hR7
$D8_k$	Th_7S_{12}	hP19
$E0_7$	FeAsS	mP24
$E1_1$	$CuFeS_2$	tI16
$E1_a$	$MgCuAl_2$	oC16
$E1_b$	$AuAgTe_4$	mP12
$E9_3$	Fe_3W_3C	cF112
$E9_4$	Al_5C_3N	hP18
$E9_a$	$FeCu_2Al_7$	tP40
$E9_b$	$FeMg_3Al_8Si_6$	hP18
$E9_c$	Mn_3Al_9Si	hP26
$E9_d$	$AlLi_3N_2$	cI96
$E9_e$	$CuFe_2S_3$	oP24
$F0_1$	NiSbS	cP12
$F5_1$	$NaHF_2$	hR4
$F5_6$	$CuSbS_2$	oP16
$F5_a$	$KFeS_2$	mC16
$H1_1$	$MgAl_2O_4$	cF56
$H2_4$	Cu_3VS_4	cP8
$H2_6$	$FeCu_2SnS_4$	tP16
$L1_0$	CuAu	tP2
$L1$	CuPt	hR32
$L1_2$	Cu_3Au	cP4
$L1_a$	Pt_3Cu	cI32
$L2_1$	Cu_2MnAl	cF16
$L2_2$	Tl_7Sb_2	cI54
$L2_a$	TiCu	tI2
L'_1	Fe_4N	cF5
$L'1_2$	$AlFe_3C$	cP5
$L'2$	Fe-C (Martensite)	tI2
$L'3$	Fe_2N	hP3
$L6_0$	$CuTi_3$	tP4

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7 Metallurgically important minerals

Table 7.1 gives data on the minerals from which the more important metals are extracted. Those minerals of major importance are shown in **bold type** in column 2. Parentheses indicate that the element is recovered as a by-product in the extraction of another metal.

The chemical formulae assigned in column 3 are given only to indicate the nature of the minerals since they are not stoichiometric chemical compounds.

The mineral-producing countries are listed in order of decreasing production in column 6, and the major metal producers in column 8.

The figure for abundance given in column 1 is the amount of the metal in parts per million of the igneous rocks of the lithosphere. The figure for metal production in column 9 refers to refined primary metal production, except where indicated as contained metal in produced ores or concentrates, or as including secondary refined production. The figure for reserves given in column 10 is the recoverable material in the reserve base that can be economically extracted or produced at the time of determination.

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Table 7.1 ORE GRADES AND SOURCES

Element abundance p.p.m.	*Minerals*	*Formulae*	*Metal content* %	*Specific gravity* g cm^{-3}	*Major mineral sources*	*Normal ore grade*	*Major metal sources*	*1983/84 World production of metal* (tonnes)	*World reserves* ('000s tonnes contained metal)
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Aluminium 81 300	**Bauxite**	Hydrous aluminium and iron oxides	25–39	2.55	Australia, Guinea, Jamaica, Brazil, USSR, Yugoslavia	25–39% Al	USA, USSR, Canada, W. Germany, Norway	15.1×10^6	20 954 000
Antimony	Senarmotite	Sb_2O_3	84	5.3	China, Bolivia, S. Africa, USSR, Mexico, Thailand	2–25% Sb	China, Turkey, Peru, Bolivia	49.6×10^3	4170
	Valentinite	Sb_2O_3	84	5.60					
	Kermesite	Sb_2S_2O	75.3	4.60					
1	**Stibnite**	Sb_2S_3	71.7	4.5–4.6					
Arsenic	(**Arsenopyrite**)	FeAsS	*40–49.9*	5.9–6.3	Chile, USA, Canada, France, Mexico, Philippines	2–15% As	USSR, USA, Sweden, France, Mexico, Chile	39 403 (as trioxide containing 76% As)	1 000
	(Orpiment)	As_2S_3	60.9	3.49					
2	(Realgar)	AsS	70	3.48–3.56					
	(**Sulpharsenides** and **Arsenides** of Cu, Pb, Au, Sn)		15–23 (in flue dusts)						
Beryllium	**Bertrandite**	$Be_4Si_2O_7(OH)_2$	15.1	2.59–2.66	Brazil, India, USSR, Argentina, USA, S. Africa	0.1–0.6% Be	USA, USSR, Brazil, Zimbabwe, Portugal, Argentina	341	0.381
	Beryl	$Be_3Al_2Si_6O_{18}$	5	2.7					
2									
Bismuth (0.2)	(Native bismuth)	Bi	100	9.7–9.8	Australia, Japan, Mexico, Peru, China	0.05–0.8% Bi in Pb, Cu, Sn ores	Australia, USA, Peru, Japan	4.3×10^3 (metal + in ores and concentrates)	92
	Bismuthinite	Bi_2S_3	81.2	6.4–6.5					
Cadmium	(in **Sphalerite**)	—	Trace to 1.66	—	Canada, USSR, Australia, Peru, USA, Mexico	0.1–0.3% Cd (in sphalerite)	USSR, Japan, USA, Canada, Belgium, W. Germany	18.4×10^3 (includes secondary)	555
(0.15)									

Calcium 36 300	**Limestone** Brines	Chiefly $CaCO_3$	40 3.6 (Variable)	2.71	Worldwide	Pure	USA, France, W. Germany	—	Vast
Cerium (25)	Bastnaesite **Monazite**	(Ce, La, Di)$(CO_3)F$ (Ce, La, Y, Th) PO_4	50 46	4.9–5.2 4.6–5.4	Australia, India, Brazil, S. Africa, USA, Malaysia	0.1–3% Ce		37×10^3 (rare earth oxides)	—
Chromium 200	**Chromite**	$FeCr_2O_4$	38.2–46.5	4.5–4.8	S. Africa, USSR, Zimbabwe, Finland, Philippines, India	20–45% Cr	USSR, USA, Japan, UK	3×10^6 (metal + alloys)	1056×10^3
Cobalt 25	**(Safflorite)** **(Skutterudite)** **(Smaltite)** **(Sphaerocobaltite)** **(Erythrite)** **(Asbolite)** **(Heterogenite)** **(Cobaltite)** **(Carrollite)** **(Linnaeite)**	$(Co, Fe)As_2$ $(Co, Ni)As_3$ $(Co, Ni)As_2$ $CoCO_3$ $(Co, Ni)_3(AsO_4)_2 \cdot 8H_2O$ Hydrous Mn oxide Hydrous cobaltic/cobaltous oxide (Co, Fe)AsS Co_2CuS_4 Co_3S_4	13–28 11–21.7 13.8–24 54 18.8–26.6 <13 Variable 28.5–35.5 35–36 58	6.9–7.3 6.5–6.9 5.7–6.8 4.1 3.06 2.8–4.4 3.44 6.0–6.3 4.8 4.8–5.0	Zaire, Cuba, Zambia, New Caledonia, Indonesia, USSR	0.1–1% Co	USSR, Australia, Canada, W. Germany (estimated order)	19789 (excl. USSR)	3595
Copper 70	Native copper **Azurite** **Malachite** **Cuprite** **Chrysocolla** Brochantite Chalcanthite Atacamite **Chalcocite** **Bornite** **Chalcopyrite** **Covellite** Enargite Tennantite Tetrahedrite	Cu $Cu_3(OH)_2(CO_3)_2$ $Cu_2(OH)_2(CO_3)$ Cu_2O $CuSiO_3 \cdot 2H_2O$ $Cu_4(SO_4)(OH)_6$ $CuSO_4 \cdot 5H_2O$ $Cu_2(OH)_3Cl$ Cu_2S Cu_5FeS_4 $CuFeS_2$ CuS Cu_3AsS_4 $Cu_8As_2S_7$ variable $(CuFe)_{12}Sb_4S_{13}$	100 55 58 88.8 36.2 56 25 59.4 79.9 63.5 34.6 66.7 45.7–49.0 57.5 var. 25.0–45.7	8.95 3.77 4.05 5.9–6.2 2.0–2.2 3.97 2.1–2.3 3.76 5.5–5.8 4.9–5.4 4.1–4.3 4.6–4.76 4.45 4.4–4.5 4.6–5.1	Chile, USA, Zambia, Zaire, USSR, Mexico, Canada, Peru	0.3–5% Cu	USA, USSR, Japan, Chile, Zambia, Canada, Belgium, W. Germany	9.6×10^6	337×10^6

* China unknown. Probably large.

Table 7.1 ORE GRADES AND SOURCES- *-continued*

Element abundance p.p.m.	*Minerals*	*Formulae*	*Metal content* %	*Specific gravity* g cm^{-3}	*Major mineral sources*	*Normal ore grade*	*Major metal sources*	*1983/84 World production of metal* (tonnes)	*World reserves* ('000s tonnes contained metal)
Gallium 15	(Gallite) (in **Bauxite**) (in Coal ash) (in Germanite) (in **Sphalerite**)	$CuGaS_2$	35.5 <0.01 <0.05 <1.85 <0.02	4.2	Canada, USA, S. Africa, Jamaica, Australia, Guinea (estimated order)	0.003–0.01% 0.001–0.05% Up to 1% Ga 0.005–0.02% (in associated minerals)	Japan, France, W. Germany, USA, Canada, China	20 25 (incl. one-third secondary as an alumina by-product)	100 (in bauxite) 6.5 (in zinc ores. Only a small percentage is economically recoverable)
Germanium 1–2	Renierite Germanite (in **Coal ash**) (in **Sphalerite**)	$(Cu, Fe)_3(Fe, Ge, Zn, Sn)(S, As)_4$ (Cu, Ge[3])(S, As)	6.4–7.8 6.0–10.2 <0.25 <0.3	4.46–4.59 4.5–4.6	Namibia, Zaire, USA	0.005 0.25% 0.03-0.3% Ge (in associated minerals)	USA, Belgium, USSR, France, Italy, W. Germany	94	2150
Gold (0.005)	**Native gold** Alloys with Hg Ag, Cu, Fe, Pd, Rh Calaverite Nagyagite Krennerite Petzite Sylvanite (Anode slime from Cu, Pb, Ag, Ni extraction)	Au $AuTe_2$ $Pb_3Au(Te, Sb)_4S_{5-8}$ $AuTe_2$ Ag_3AuTe_2 $(Ag, Au)Te_2$	74–99.9 39–43.6 7.4–10.2 30.7–43.9 19.0–25.4 24.2–29.9	19.3 9.0–9.3 7.4 8.6 8.7–9.02 8.16	S. Africa, USSR, USA, Canada, Brazil, Australia	0.0007–0.003% Au	S. Africa, USSR, Canada, USA, China, Brazil	1466	39815
Hafnium (4.5)	(in **Zircon**) (in Cyrtolite)		0.5–2.0 <31		USA, Australia	0.5–2% Hf Up to 31% Hf (in associated minerals)	USA	90 (estimate)	-

Indium	(in **Sphalerite**)		<0.01		USA, Canada	Up to 0.1% In	Canada, Japan,	50	1700
	(in **Smithsonite**)		<0.01		Australia, Sweden,	(in associated	USA, W. Germany,		
0.11					Peru, China	*minerals*)	**Belgium**		
Iron	Siderite	$FeCO_3$	48.3	3.48–3.96	USSR, Brazil,	25–70% Fe	USSR, Brazil,	442×10^6	66×10^9
	Goethite	$HFeO_2$	63.0	3.3–4.3	Australia, China,		Australia, USA,	(in mine	
50 000	**Hematite**	Fe_2O_3	69.9	4.9–5.3	USA		Canada, China,	production)	
	Limonite	Hydrous iron oxides	60.0	2.7–4.3			India, S. Africa		
	Magnetite	$FeFe_2O_4$	72.4	5.2					
	Pyrite	FeS_2	46.5	4.8–5.02					
	Pyrrhotite	$Fe_{1-x}S$ ($x=0$–0.2)	58.0–63.5	4.4–4.6					
	(Ilmenite)	$FeTiO_3$	1–13.5	4.7					
Lead	Cerussite	$PbCO_3$	77.0	6.55	USA, Australia,	2–14% Pb	USA, USSR,	5.3×10^6	96×10^6
	Anglesite	$PbSO_4$	68.0	6.38	USSR, Canada,		W. Germany, Japan,		
15	**Galena**	PbS	86.6	7.4–7.6	S. Africa, Yugoslavia		UK, Canada		
Lithium	**Amblygonite**	$(Li, Na)(Al)PO_4(F, OH)$	4.8	3.0–3.1	Bolivia, USA,	0.2–1% Li	USA, USSR	7239*	1936
	Eucryptite	$LiAlSiO_4$	5.5	2.67	Australia, Zimbabwe,			(from	(W. World
30	**Lepidolite**	$K(Li, Al)_3(Si, Al)_4O_{10}(F, OH)$	2.0	2.8–3.3	Namibia, USSR			concentrates	only)
	Petalite	$Li(Al, Si_4)O_{10}$	2.3	2.4				and brine)	
	Spodumene	$LiAlSi_2O_6$	3.7	3.1–3.2					
	Brines		~0.05						
Magnesium	Dolomite	$CaMg(CO_3)_2$	22	2.8–2.9	China, USSR,	0.1–0.2% Mg	USSR	295×10^3	2530×10^6
	Brines				N. Korea, Brazil,			(primary	
20 900					Australia			metal)	
Manganese	Rhodochrosite	$MnCO_3$	47.8	3.7	S. Africa, USSR,	30–54% Mn	USSR, S. Africa,	8097×10^3	929×10^3
	Hausmannite	$MnMn_2O_4$	71.6	4.8	Brazil, Australia,		Brazil, Gabon,	(contained in	
1000	**Psilomelane**	$BaMn_2Mn_8O_{16}(OH)_4$	<51	4.7	India, China		Australia, India	mine	
	Pyrolusite	βMnO_2	63	4.4–5.0				production)	
	Manganite	$MnO(OH)$	62	4.3					
	Braunite	Oxide of Mn and Si	51–63	4.7–4.8					
Mercury	**Cinnabar**	HgS	86.2	8.1	Spain, Yugoslavia,	0.2–1% Hg	USSR, Spain,	177.5×10^3	3960
					USSR, China,		USA, China,	(76 lb flasks)	
(0.03)					USA		Algeria, Mexico		
Molybdenum	(Wulfenite)	$PbMoO_4$	24.6–33.3	6.5–7.0	USA, Chile,	0.002–0.2% Mo	USA, Chile,	166.7×10^3	5519
	Molybdenite	MoS_2	59.9	4.6–4.7	USSR, Canada,		China, USSR,	(productive	
1	Molybdite	MoO_3	66.7	4.5	Mexico		Canada, Peru	capacity)	

Table 7.1 ORE GRADES AND SOURCES—*continued*

Element abundance p.p.m.	*Minerals*	*Formulae*	*Metal content* %	*Specific gravity* g cm^{-3}	*Major mineral sources*	*Normal ore grade*	*Major metal sources*	*1983/84 World production of metal* (tonnes)	*World reserves* ('000s tonnes contained metal)
Nickel	**Garnierite**	$(Ni, Mg)_3Si_2O_5(OH)_4$	<46	2.2–2.8	Cuba, Canada,	0.1–2% Ni	USSR, Canada,	717×10^3	52 740
	Pentlandite	$(Fe, Ni)_9S_8$	34–35	4.6–5.0	USSR, Indonesia,		Japan, Australia,		
80					Australia, S. Africa		USA, Norway		
Niobium	**Columbite**	$(Fe, Mn)(Nb, Ta)_2O_6$	24–55	5.2–6.4	Brazil, USSR,	0.4–3% Nb	Brazil, Canada,	10 653	4 126
	Pyrochlore	$NaCnNb_2O_6F$	16–51	3.77–4.95	Canada, Nigeria,		Thailand, Nigeria,	(contained in	
(25)					Zaire, Thailand		Australia, Zaire	mine production)	
Platinum	**Native platinum**	Pt	60–90	14–19	S. Africa, Columbia,	1–4 g/t Pt	USSR, S. Africa,	~75	30 750
group	**Sperrylite**	$PtAs_2$	52.5–56.6	10.58	Canada, USSR,		Canada		
metals*	Braggite	PtS	58–60	10.0	USA				
	Cooperite	PtS	80–86	9.5					
(0.005)	Alloyed with other PtGp, CuNiAu								
Potassium	Carnalite	$KMgCl_3.6H_2O$	14	1.60	USSR, Canada,	10–30% K	USA, W. Germany	30×10^6	9 150 000
	Sylvite	KCl	52.4	1.99	USA, W. Germany,	0.5–16% K	Japan, USSR	(estimate	(as K_2O)
27 000	Brines		0.5–16.6		E. Germany, France			Potash K_2O)	
Rhenium	(in **Molybdenite**)		<1.0		Chile, USA,	0.001–1% Re	USA, Chile,	13.4	2.995
					Canada, USSR,	in molybdenite	USSR, W. Germany,	(in	
(0.001)					Peru		Sweden, Belgium	concentrates)	
Selenium	(Anode slime from copper refining)	—	3–28	—	Chile, USA, Canada, Zambia, Zaire, Mexico	3–20% Se in anode slime	Canada, Japan, USA, Belgium, Sweden	1 400 (excl. USSR, China)	83
0.09									
Sodium	**Halite**	NaCl	39.4	2.17	Worldwide	Pure	USA, USSR,	—	Vast
	Brines		~10.0			~10% Na	Germany, UK,		
28 300	Sea-water		~1.0			~1% Na	Japan, Australia		

Silicon 277 000	**Quartz**	SiO_2	46.7	2.65	Worldwide	Pure	USA, USSR†, Norway, France, Yugoslavia, Portugal	54 000	Vast
Silver (0.04–0.1)	Native silver **Argentite** **Polybasite** **Proustite** **Pyrargarite** **Stephanite** (By-product of Pb, Cu, Zn, Au, Ni, Sn)	Ag Ag_2S $(Ag, Cu)_{16}Sb_2S_{11}$ Ag_3AsS_3 Ag_3SbS_3 Ag_5SbS_4	95–98.5 87 58–74.3 64.5–65.4 59.5–60.8 68.3	10.1–11.1 7.2–7.4 6.1 5.5–5.64 5.77–5.87 6.25	Mexico, Peru, USSR, USA, Canada, Australia	0.01–0.1% Ag	Canada, USSR, Mexico, USA, Peru, Australia	12 535 (primary) 1 800 (secondary)	244
Tantalum (2.1)	**Tantalite** (in Tin slags)	$(Fe, Mn)(Ta, Nb)_2O_6$	36–56 ~7	5.3–7.3	Thailand, USSR, Australia, Niger, Canada, Zaire	0.1–0.5% Ta	Thailand, USSR, Brazil, Australia, Malaysia, Zaire	900	26.275
Tellurium 0.01	(Anode slime from Cu refining) (Flue dusts Cu, Ag, Au, Pb, Bi) Pb and Au ores	—	<8		Chile, USA, Zambia, Zaire, Canada	Up to 8% in anode slimes	Japan, USA, Canada, Peru, Belgium, USSR	290 (W. World only)	21 880 (recovered from economic copper and gold deposits)
Thallium 1.3	(By-product from Zn, Cd refining) (From flue dusts smelting Pb, Cu, Zn ores)	—	0.1–0.5	—	USA, Belgium, Germany, USSR (estimated order)	0.05–0.1% Tl (in flue dusts)	USA, Belgium, Germany, USSR	—	—
Thorium 11.5	Thorianite Thorite Monazite	ThO_2 $ThSiO_4$ $(Ce, La, Y, Th)(PO_4)$	35–83 71 5.1–10.8	9.7 4.5–5.4 4.6–5.4	India, Brazil, Australia, Sri Lanka, Indonesia, USA	0.1–1% Th	Australia, Brazil	37×10^3 (rare earth oxides)	—
Tin 2	**Cassiterite**	SnO_2	78.6	6.8–7.1	Malaysia, Indonesia, Thailand, Australia, Bolivia	0.5–4% Sn (hard rock) >0.002% Sn (alluvial)	Malaysia, Indonesia, Thailand, USSR, China, Brazil	197×10^3	3 140

* Includes: platinum, palladium, iridium, osmium, rhodium and ruthenium. † Refinery capacities. No data on metal production.

Table 7.1 ORE GRADES AND SOURCES—*continued*

Element abundance p.p.m.	*Minerals*	*Formulae*	*Metal content* %	*Specific gravity* g cm^{-3}	*Major mineral sources*	*Normal ore grade*	*Major metal sources*	*1983/84 World production of metal* (tonnes)	*World reserves* ('000s tonnes contained metal)
Titanium	**Ilmenite**	$(Fe, Mg, Mn)TiO_3$	31.2–33.6	4.5–5.0	In ilmenite: S. Africa, India, China	2–30% Ti	USSR, USA, Japan, UK, China	75.6×10^3	In ilmenite: 123 000
	Rutile	TiO_2	60	4.23	In rutile: Brazil, Australia, India				In rutile: 471 000
4 400									
Tungsten	Ferberite	$FeWO_4$	60	7.2–7.5	China, Canada, USSR, USA, Australia	0.4–3% W	China, Canada, USSR, USA, Australia	42 180 (in concentrates)	2 798
	Hubnerite	$MnWO_4$	60	7.2–7.5					
(3)	**Scheelite**	$CaWO_4$	59–64	5.9–6.1					
	Wolframite	$(Fe, Mn)WO_4$	60	7.1–7.5					
Uranium	Brannerite	Oxide of Ti, U, Ca, minor Y, Th, Fe	37	4.5–5.4	Australia, USA, S. Africa, Canada, Niger*	0.1–0.3% U	Canada, USA, S. Africa, Namibia, Niger, France**	37 218 (in concentrates)	2 239
4	**Carnotite**	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$	52–54	<4.7					
	Uraninite Pitchblende	UO_2 (normally $U_{3-4}O_8$)	54–80.7	6.5–10.8					
	Autunite	$Ca(UO_2)_2(PO_4)_2 \cdot 10–12H_2O$	48–51	3.1–3.2					
	Torbernite	$Cu(UO_2)_2(PO_4)_2 \cdot 8–12H_2O$	47–50.6	3.2					
	Coffinite	Silicate of U	41–60	2.2–5.1					
Vanadium	**(Carnotite)**	$K_2(UO_2)_2(VO_4)_2 \cdot 3H_2O$	11.5	<4.7	USSR, S. Africa, China, USA, Finland, Australia	0.4–2% V	USA, S. Africa†, Japan, USSR	29.5×10^3	4 354
	Descloizite	$(ZnCu)Pb(VO_4)(OH)$	9.0–13.0	~6.2					
150		$2K_2O \cdot 2Al_2O_3(Mg, Fe)O$							
	Roscoelite	$3V_2O_5 \cdot 10SiO_2 \cdot 4H_2O$	11.8	2.97					
	Vanadinite	$Pb_5(VO_4)_3Cl$	9.5–10.6	6.5–7.1					
	Patronite	VS_4	28.5	—					
	(Associated with iron ores)		0.8–0.9						
Zinc	Smithsonite	$ZnCO_3$	29.0–52.0	4.0–4.45	Canada, USSR, Australia, Peru, Mexico, USA	5–10% Zn	USSR, Japan, Canada, W. Germany, USA, Australia	6.46×10^6 (world smelter production)	169 000
	Hemimorphite	$Zn_4Si_2O_7(OH)_2 \cdot H_2O$	54	3.45					
50	**Sphalerite**	(Zn, Fe)S	51–67	3.9–4.1					
Zirconium	Baddeleyite	ZrO_2	71.4–73.4	5.4–6.0	Australia, S. Africa, USSR, USA, Brazil	<10% Zr	Japan, France, USA	355×10^3	21 100
	Zircon	$ZrSiO_4$	49.7	4.2–4.7					
220									

* Reasonably assured W. World reserves. ** W. World production. † Vanadium from mineral sources, petroleum residues, ashes and catalysts.

8 Thermochemical data

Except where otherwise indicated, the data given in these tables have been selected from three main sources: 'Selected Values of the Thermodynamic Properties of the Elements', by R. Hultgren, P. O. Desai, D. T. Hawkins, M. Gleiser and K. K. Kelley, and by the same authors, 'Selected Values of the Thermodynamic Properties of Binary Alloys'; also 'Metallurgical Thermochemistry', 5th edn., by O. Kubaschewski and C. B. Alcock. These works represent the most authoritative compilations of critically assessed data presently available, to which reference should be made for original sources or details of assessment.

8.1 Symbols

θ_m = melting point in °C
θ_e = boiling or sublimation point in °C at 760 mmHg
θ_t = transition temperature in °C
θ_s = sublimation point in °C
T = absolute temperature in K
L_m = latent heat of fusion
L_e = latent heat of vaporization
L_t = latent heat of transition
L_s = latent heat of sublimation
} in kJ mol^{-1} (or kJ g-atom^{-1}) or in Jg^{-1}
ΔV_m = volume change during melting $[(V_{liq}-V_{solid})/V_{solid}]\%$
ΔH_{298} = heat of formation at 298 K (25°C) in kJ mol^{-1} (or kJ g-atom^{-1}) or in Jg^{-1}. (The value of a heat evolved during a reaction is taken to be negative)
ΔG = maximum work (change of free energy) in kJ mol^{-1} (or kJ g-atom^{-1})
S_{298} = standard entropy at 298 K (25°C) in Jk^{-1} mol^{-1} (or J g-atom^{-1})

p (mm Hg) = vapour or dissociation pressure in mmHg
N_1 = mol fraction of the first component
N_2 = mol fraction of the second component
C_p = specific heat in J k^{-1} mol^{-1}
c_p = specific heat in J g^{-1} k^{-1}

8.2 Changes of phase

Table 8.1 ELEMENTS
Latent heats and temperatures of fusion, vaporization and transition, and change in volume on melting

Element	*Melting point* θ_m °C	*Boiling point* θ_e °C	θ_t °C	L_m *at m.p.* kJ g-atom^{-1} *or* mol^{-1}	L, kJ g-atom^{-1} *or* mol^{-1} L_s *at 25 C*	L_e *at b.p.*	L_t kJ g-atom^{-1} *or* mol^{-1}	ΔV_m %
Ag	960.8	2200	— —	11.09	284.2	257.8	—	(3.8)
Al	660.1	2520	—	10.47	321.9	290.9	—	6.5
Am	—	2600	—	—	—	238.6	—	—
As	817	603	—	$As_4 = 4As + 118.1$ kJ			—	10
Au	1063	2860	—	12.78	378.9	342.4	—	5.1

Table 8.1 ELEMENTS—*continued*

Element	*Melting point* θ_m °C	*Boiling point* θ_e °C	θ_t °C	L_m *at m.p.* kJ g-atom^{-1} *or* mol^{-1}	L, kJ g-atom^{-1} *or* mol^{-1}		L_t kJ g-atom^{-1} *or* mol^{-1}	ΔV_m %
					L_s *at 25 C*	L_v *at b.p.*		
B	2 180	3 800	—	22.6	577.8	—	—	—
Ba	729	1 700	370	7.66	(192)	177.1	0.59	—
Be	1 287	2 470	1 254	12.22	324.4	292.6	2.55	—
Bi	271	1 564	—	10.89	207.2	179.2	—	−3.35
Br_2	−7.3	58	—	10.55	—	30.56	—	—
C (graph)	(3 800)	(5 000)	—	—	712	—	1.90 diam→ graph	—
Ca	843	1 484	464	8.36	176.2	150.7	0.25	—
Cd	320.9	767	—	6.41	112.2	99.6	—	4.0
Ce	798	3 430	726	5.23	(407)	376.0	(2.9)	—
Cl_2	−101.0	−34.1	—	6.41	—	20.423	—	—
Co	1 495	2 930	440 1 120	(15.5)	425	—	0.25, 0.92	3.5
Cr	1 857	2 672	—	(20.9)	397	342.1	—	—
Cs	29.8	700	—	2.09	78.7	66.6	—	2.6
Cu	1 083.4	2 560	—	13.02	341.2	304.8	—	4.2
Dy	1 409	2 560	1 384	—	—	—	—	—
Er	1 522	2 860	1 470	—	—	—	—	—
Eu	826	1 490	—	—	—	—	—	4.8
F_2	−219.6	−188.0	—	1.595	—	6.531	—	—
Fe	1 536	2 860	914 1 391	15.2	398.6	340.4	β5.11* γ0.563* γ→δ0.84	3.5
Ga	29.7	2 420	—	5.594	285.0	270.5	—	−3.2
Gd	1 312	3 290	1 260	—	—	—	—	—
Ge	937	2 830	—	36.8	383.8	327.8	—	−5.1
H_2	−259.2	−252.5	—	0.117	—	0.909	—	(12.3)
Hf	2 227	4 600	1 940	24.07	611.3	571.1	(6.91)	—
Hg	−38.87	357	—	2.324	—	61.1	—	3.7
I_2	113.6	183	—	15.78	62.4	41.9	—	21.6
In	156.4	2 070	—	3.27	242.8	232.4	—	2.0
Ir	2 443	4 430	—	(26)	669.9	612.5	—	—
K	63.2	779	—	2.39	90.0	79.5	—	2.55
La	920	(3.420)	868	(8.37)	422.9	402.4	(2.9)	—
Li	181	1 324	—	2.93	161.6	147.8	—	(1.65)
Mg	649	1 090	—	8.79	146.5	127.7	—	4.12
Mn	1 244	2 060	710 1 090 1 136	(14.7)	291.0	231.1	2.22 2.22 1.80	(1.7)
Mo	2 620	4 610	—	35.6	664.5	590.3	—	—
N_2	−210.0	−195.8	−237.5	0.720	—	5.581	0.229 0	7.3
Na	97.8	883	—	2.64	108.9	98.0	—	2.5
Nb	2 467	4 740	—	29.3	722.2	683.7	—	—
Nd	1 016	3 070	862	7.14	323.6	—	2.98	—
Ni	1 453	2 910	358	17.16	429.6	374.3	0.58	4.5
Np	637	—	280, 577	—	—	—	—	—
O_2	−218.8	−183.0	−249.5 −229.4	0.445	—	6.8	0.093 8 0.743 6	7.4
Os	3 030	5 030	—	—	791	—	—	—
P (yellow)	44.1	280	—	2.64	140.7(P_2) 58.8(P_4)	51.9(P_4)	17.6 yell.→red	3.5
Pb	327.4	1 750	—	4.81	196.4	178.8	—	3.5
Pd	1 552	2 940	—	(16.7)	377.2	361.7	—	—
Po	246	965	(100)	—	—	100.9	—	—
Pr	932	3 510	798	(11.3)	—	—	—	—

*Only together with the tabulated heat capacities of iron: Table 8.10.

Table 8.1 ELEMENTS—*continued*

Element	*Melting point* θ_m °C	*Boiling point* θ_e °C	θ_t °C	L_m *at m.p.* kJ g-atom^{-1} *or* mol^{-1}	L, kJ g-atom^{-1} *or* mol^{-1}		L_t kJ g-atom^{-1} *or* mol^{-1}	ΔV_m %
					L_s *at 25 C*	L_v *at b.p.*		
Pt	1 769	4 100	—	(19.7)	545.0	469.2	—	—
Pu	640	3 420	122, 205, 318, 452, 476	2.9	343.7	352.0	3.39, 0.59, 0.54, 0.08, 1.84	−2.5
Ra	700	1 500	—	—	—	—	—	—
Rb	38.8	688	—	2.198	87.5	75.8	—	2.5
Re	3 180	5 690	—	33.5	779.2	(712)	—	—
Rh	1 966	3 700	(1 030)	(22.6)	556.0	(494)	—	—
Ru	2 250	4 250	—	—	—	—	—	—
S (rhomb.)	112.8	444.5	95.5	1.235	—	*	0.38	(5.1)
S (mon.)	119.0	—	—	—	—	—	—	—
Sb	630.5	1 590	—	19.89	—	(167)(Sb_2)	—	0.8
Sc	1 538	(2 870	1 334	—	376.0	—	—	—
Se (met.)	220.5	685	—	6.28	—	95.5(Se_2)	—	15.8
Si	1 412	3 270	—	50.66	450.1	384.8	—	(−10)
Sm	1 072	1 803	917	8.92	207.2	165.0	3.10	—
Sn	231.9	2 625	13	7.08	302.3	296.4	2.22	2.3
Sr	770	1 375	235, 540	(8.4)	177.1	154.5	—	—
Ta	3 015	5 370	—	(24.7)	782.5	—	—	—
Tb	1 360	3 220	1 290	—	—	—	—	—
Te	450	988	—	17.6	171.6(Te_2)	104.7(Te_2)	—	4.9
Th	1 750	4 790	1 325	—	576.1	(511)	—	—
Ti	1 667	3 285	882	(17.5)	469.3	425.8	3.34	—
Tl	304	1 473	234	4.3	180.9	166.2	0.38	2.2
U	1 132	4 400	662, 770	12.5	482.2	417.4	2.85, 4.878	—
V	1 902	3 410	—	16.74	510.2	457.2	—	—
W	3 400	5 555	—	35.2	847.8	(737)	—	—
Y	1 530	3 300	1 485	11.43	424.9	367.6	5.0	—
Yb	824	1 194	760	—	—	—	—	—
Zn	419.5	907	—	7.28	129.3	114.3	—	4.7
Zr	1 852	4 400	852	(19.3)	612.1	579.9	3.85	—

* L_e at b.p.: S_2, 106.4 (625 °C); S_4, 96.0 (625 °C); S_6, 66.2 (527 °C); S_8, 63.1 (490 °C).
ΔV_m, ref. 4.

Table 8.2a INTERMETALLIC COMPOUNDS

Latent heats and temperatures of fusion

If an intermetallic phase is completely disordered, the entropy of fusion (L_m/T_m) can generally be calculated additively from the entropies of fusion of the components. If it is completely ordered, $-19.146\,(N_1 \log N_1 + N_2 \log N_2)$ is as a rule to be added to the calculated entropy of fusion.

Phase	N_2 10^{-2}	θ_m °C	L_m	
			kJ g-atom^{-1}	J g^{-1}
δ-Ag-Cd	67.5	592	8.46 ± 0.42	76.2
γ-Ag-Zn	61.8	664	7.79 ± 0.33	95.5
δ-Ag-Zn	72.1	632	8.75 ± 0.42	131.5
Al_2Cu	33.3	590–605	12.6 ± 0.8	320.3
γ-Al-Mg	57.2	455	8.8 ± 0.8	346.7
AuCd	50.0	627	8.96 ± 0.50	57.8
$AuPb_2$	66.7	254–300	8.00 ± 0.75	39.4
AuSn	50.0	418	12.81 ± 0.33	81.2
β-Au-Zn	50.0	760	12.31 ± 0.54	93.8
ε-Au-Zn	88.9	490	7.45 ± 0.38	93.4

Table 8.2a INTERMETALLIC COMPOUNDS—*continued*

Phase	N_2 10^{-2}	θ_m °C	L_m kJ g-atom^{-1}	L_m J g^{-1}
Bi-In	50.0	110	—	7.33
$Bi-In_2$	66.7	—	—	4.81
δ-Bi-Tl	40.0	214	7.24±0.25	35.2
δ-Cd-Cu	38.4	555	9.71±0.21	103.8
δ-Cd-Cu	40.0	562	9.55±0.21	103.0
Cd–Mg	25.0	349–368	5.86	56.5
	50.0	415–430	6.05	87.9
	75.0	489–515	6.91	152.4
Cd_2Na	33.3	385	7.87±0.63	95.5
CdSb	50.0	456	16.0±0.33	136.9
GaLi	50.0	700–760	16.7±0.8	435.4
GaSb	50.0	703	25.1±1.7	131.0
Hg_2Na	33.3	350	8.8±0.8	63
γ-Hg–Tl	28.6	14.5	2.01±0.13	10.0
InLi	50.0	630	13.4±0.8	219.8
InSb	50.0	425	24.7±0.8	205.2
KNa_2	66.7	7	2.9±0.1	103.4
Mg_2Pb	33.3	550	13.4±1.3	155
$MgZn_2$	66.7	590	14.3±0.8	260
Na_5Pb_2	28.5	400	7.18±0.5	95
NaPb	50.0	368	8.4±0.4	71
β Na–Pb	71.5	320	7.1±0.4	46
NaTl	50.0	250–305	8.4±0.8	73.7
γ-Pb–Tl	87.5	329–339	5.23±0.17	25.5
γ-Pb–Tl	63.0	379-	5.65±0.17	27.6

Ref. 3.

Table 8.2b INTERMETALLIC COMPOUNDS
Latent heats and temperatures of transition
The method of measurement is subject to error. Most of the reported values are probably too low.

Phase	N_2 10^{-2}	*Transition*	θ_t °C	L_t J g-*atom*$^{-1}$
β-Ag–Cd	50.0	β′–β	211	712
AgZn	50.0	order–disorder	258	2449
AuCu	50.0	order–disorder	408	1779
$AuCu_3$	75.0	order–disorder	390	1214
$AuSb_2$	66.7	β–γ	355	335
Cd_3Mg	27.0	order–disorder	95	963
CdMg	50.0	order–disorder	50–260	2638
$CdMg_3$	75.3	order–disorder	80–165	1256
CrFe	52.0	σ–α	805	1633
CuPt	50.0	order–disorder	800	3810
Cu_3Pt	20.0	order–disorder	610	1968
β-Cu–Zn	50.0	β′–β	470	2219
$FeNi_3$	74.3	order–disorder	506	2721
$MnNi_3$	75	order–disorder	(500)	3119
Pd_3Sb	25	β–β′	950	10300
Zn_3Sb_2	40.0	—	409–455	6.071

Ref. 3.

Table 8.3 OTHER METALLURGICALLY IMPORTANT COMPOUNDS
Latent heats and temperatures of fusion, vaporization and transition
(If not stated otherwise, the values of the latent heats are for the temperatures of transition, fusion, evaporation or sublimation, respectively. Boiling and sublimation points are for 1 atm pressure of the undissociated molecules)

Compound	$\theta_m, \theta_e, \theta_s$ or θ_t °C	L_m, L_e, L_s or L_t kJ mol^{-1}
	Carbides	
CH_4	θ_m, −182.5	L_m, 0.938
	θ_e, −161.4	L_e, 8.323
Fe_3C	θ_t, 190	L_t, 0.75
	θ_m, 1 227	L_m, 51.62
Mn_3C	θ_t, 1 037	L_t, 15.1
	Halides	
AgCl	θ_m, 455	L_m, 13.0
	θ_e, 1 564	L_e, 177.9
AgBr	θ_m, 430	L_m, 9.2
	θ_e, 1 560	L_e, 192.2
AgI	θ_m, 557	L_m, 9.42
	θ_e, 1 506	L_e, 144.24
	Hex.→cub.	
	θ_t, 147	L_t, 6.07
AlF_3	θ_s, 1 280	L_s, 280.5
Al_2Cl_6	θ_m, 193	L_m, 71.2
	θ_s, 160	L_s, 111.8
Al_2Br_6	θ_m, 97	L_m, 22.6
	θ_e, 255	L_e, 45.6
AlI_3	θ_m, 191	L_m, 16.3
	θ_e, 385	L_e, 64.5
AsF_3	θ_m, −6	L_m, 10.38
	θ_e, 58	L_e, 29.7
AsF_5	θ_m, −80	L_m, 11.47
	θ_e, −53	L_e, 20.9
$AsCl_3$	θ_m, −16	L_m, 10.13
	θ_e, 130	L_e, 31.4
$AsBr_3$	θ_m, 31	L_m, 11.7
	θ_e, 221	L_e, 47.7
AsI_3	θ_m, 142	L_m, 9.2
	θ_e, 424	L_e, 59.5
BaF_2	θ_m, 1 290	L_m, 28.5
	θ_e, 2 382	L_e, 270
$BaCl_2$	θ_m, 962	L_m, 16.7
	θ_t, 922	L_t, 17.2
$BaBr_2$	θ_m, 854	L_m, 31.4
BaI_2	θ_m, 711	L_m, 26.4
$BeCl_2$	θ_m, 415	L_m, 8.7
	θ_t, 403	L_t, 16.8
	θ_e, 532	L_e, 104.7
$BeBr_2$	θ_m, 488	L_m, 18.9
	θ_e, 511	L_e, 100.0
	θ_s, 473	L_s, 125.6
BeI_2	θ_m, 480	L_m, 20.9
	θ_e, 482	L_e, 96.3
	θ_s, 488	L_s, (79.5)
$BiCl_3$	θ_m, 230	L_m, 23.9
	θ_e, 441	L_e, 72.4
$BiBr_3$	θ_m, 218	L_m, 21.8
	θ_e, 461	L_e, 75.4
CF_4	θ_m, −183.6	L_m, 0.701
	θ_e, −151	L_e, 13.063
CBr_4	θ_m, 90	L_m, 3.957
	θ_t, 47	L_t, 5.95
	θ_e, 190	L_e, 44.4
CCl_4	θ_m, −23	L_m, 2.51
	θ_e, 77	L_e, 30.6
CaF_2	θ_m, 1 418	L_m, 29.7
	θ_e, 2 510	L_e, 312.2
	θ_t, 1 151	L_t, 4.77

Compound	$\theta_m, \theta_e, \theta_s$ or θ_t °C	L_m, L_e, L_s or L_t kJ mol^{-1}
	Halides–continued	
$CaCl_2$	θ_m, 772	L_m, 28.5
$CaBr_2$	θ_m, 741	L_m, 28.9
CaI_2	θ_m, 779	L_m, (42)
CdF_2	θ_m, 1 072	L_m, 22.6
	θ_e, 1 750	L_e, 225.2
$CdCl_2$	θ_m, 568	L_m, 30.1
	θ_e, 961	L_e, 125.2
$CdBr_2$	θ_m, 565	L_m, 33.5
	θ_e, 863	L_e, 113.0
CdI_2	θ_m, 390	L_m, 20.9
	θ_e, 796	L_e, 106.3
$CeCl_3$	θ_m, 817	L_m, 53.6
$CeBr_3$	θ_m, 732	L_m, 51.9
CeI_3	θ_m, 760	L_m, 51.1
$CoCl_2$	θ_m, 740	L_m, 59.0
	θ_e, 1 025	L_e, 157.4
$CrCl_2$	θ_m, 815	L_m, 31.4
	θ_e, 1 304	L_e, 198.9
$CrCl_3$	θ_s, 945	L_s, 237.8
CsF	θ_m, 703	L_m, 21.8
	θ_e, 1 210	L_e, 155.7
CsCl	θ_m, 646	L_m, 20.5
	θ_e, 1 300	L_e, 159.9
	θ_t, 469	L_t, 2.5
CsBr	θ_m, 636	L_m, 23.66
	θ_e, 1 300	L_e, 150.7
CsI	θ_m, 621	L_m, 23.9
	θ_e, 1 280	L_e, 150.3
CuCl	θ_m, 430	L_m, 7.5
CuBr	θ_m, 488	L_m, (9.6)
CuI	θ_m, 588	L_m, (10.9)
$FeCl_2$	θ_m, 677	L_m, 43.1
	θ_e, 1 026	L_e, 126.4
$FeCl_3$	θ_m, 304	L_m, (43.1)
	θ_e, 315	L_e, 60.7 (Fe_2Cl_6)
FeI_2	θ_t, 375	L_t, 0.83
	θ_m, 590	L_m, 44.8
	θ_e, 935	L_e, 111.8
$GaCl_3$	θ_m, 78	L_m, 11.5
	θ_e, 302	L_e, 62.8
Ga_2Cl_6	θ_e, 201	L_t, 44.0
$GaBr_3$	θ_m, 122	L_m, 11.7
	θ_e, 314	L_e, 58.6
Ga_2Br_6	θ_e, 292	L_e, 50.2
GaI_3	θ_m, 212	L_m, 16.3
	θ_e, 349	L_e, 67.8
Ga_2I_6	θ_e, 462	L_e, 82.5
$GeCl_4$	θ_e, 84	L_e, 29.4
$GeBr_4$	θ_e, 189	L_e, 36.0
HF	θ_m, −83	L_m, 3.94
HCl	θ_m, −114.2	L_m, 1.99
	θ_e, −85.1	L_e, 16.161
HBr	θ_m, −86.9	L_m, 2.407
	θ_e, −67	L_e, 17.626
HI	θ_m, −50.8	L_m, 2.872
	θ_e, −35.4	L_e, 19.778
$HfCl_4$	θ_s, 316	L_s, 99.65
$HgCl_2$	θ_m, 278	L_m, 19.47
	θ_e, 304	L_e, 59.0
$HgBr_2$	θ_m, 238	L_m, 18.0
	θ_e, 319	L_e, 59.0

Table 8.3 OTHER METALLURGICALLY IMPORTANT COMPOUNDS—*continued*

Compound	θ_m, θ_e, θ_s or θ_t °C	L_m, L_e, L_s or L_t kJ mol^{-1}
	Halides—continued	
HgI_2 (yellow)	θ_m, 250	L_m, 18.8
	yellow→red	
	θ_t, 127	L_t, 2.72
HgI_2 (red)	θ_m, 256	L_m, 19.3
	θ_e, 354	L_m, 59.9
InCl	θ_m, 225	L_m, 9.2
	θ_e, 608	L_e, 88.4
$InCl_3$	θ_s, 498	L_s, 158.3
InBr	θ_m, 275	L_m, 24.3
	θ_e, 660	L_e, 95.0
$InBr_2$	θ_e, 630	L_e, 82.5
$InBr_3$	θ_s, 371	L_s, 108.4
InI	θ_m, 365	L_m, 22.4
	θ_e, 770	L_e, 96.7
IrF_6	θ_m, 44	L_m, 5.0
	θ_e, 53	L_e, 27.2
KF	θ_m, 857	L_m, 28.26
	θ_e, 1 510	L_e, 186.7
KCl	θ_m, 772	L_m, 26.6
	θ_e, 1 407	L_e, 162.4
KBr	θ_m, 740	L_m, 25.6
	θ_e, 1 383	L_e, 155.3
KI	θ_m, 685	L_m, 24.07
	θ_e, 1 330	L_e, 145.3
LiF	θ_m, 848	L_m, 26.8
	θ_e, 1 681	L_e, 214
LiCl	θ_m, 610	L_m, 19.89
	θ_e, 1 382	L_e, 150.7
LiBr	θ_m, 550	L_m, 17.6
	θ_e, 1 310	L_e, 148.2
LiI	θ_m, 469	L_m, 14.7
	θ_e, 1 171	L_e, 170.8
MgF_2	θ_m, 1 263	L_m, 58.2
	θ_e, 2 332	L_e, 292.2
$MgCl_2$	θ_m, 714	L_m, 43.1
	θ_e, 1 418	L_e, 136.9
$MnCl_2$	θ_m, 650	L_m, 37.7
	θ_e, 1 190	L_e, 123.9
MoF_5	θ_e, 214	L_e, 51.9
MoF_6	θ_m, 17	L_m, 4.2
	θ_e, 34	L_e, 28.1
$MoCl_5$	θ_m, 194	L_m, 34
	θ_e, 268	L_e, 68.8
NaF	θ_m, 992	L_m, 32.7
	θ_e, 1 710	L_e, 216.9
NaCl	θ_m, 801	L_m, 28.1
	θ_e, 1 465	L_e, 170.4
NaBr	θ_m, 750	L_m, 26.2
	θ_e, 1 392	L_e, 38.0
NaI	θ_m, 660	L_m, 23.7
	θ_e, 1 304	L_e, 159.5
NbF_5	θ_m, 77	L_m, 12.1
	θ_e, 233	L_e, 52.3
$NbCl_5$	θ_m, 205	L_m, 28.9
	θ_e, 250	L_e, 54.8
$NdCl_3$	θ_m, 760	L_m, 50.2
$NdBr_3$	θ_m, 684	L_m, 45.2
NH_4Cl	θ_t, 184	L_t, 4.3
NH_4Br	θ_t, 138	L_t, 3.2
$NiCl_2$	θ_m, 1 030	L_m, 77.5
$NiCl_2$	θ_s, 970	L_s, 225.3
$NiBr_2$	θ_s, 919	L_s, 224.8
NpF_6	θ_m, 54	L_m, 17.6
	θ_e, 55	L_e, 30.1
OsF_5	θ_e, 226	L_e, 65.7
OsF_6	θ_m, 33	L_m, 7.5
	θ_e, 47.5	L_e, 28.1
PCl_3	θ_m, −92	L_m, 4.5
	θ_e, 74	L_e, 30.6
PCl_5	θ_s, 163	L_s, 64.9
PBr_3	θ_e, 174	L_e, 39.8
PbF_2	θ_m, 818	L_m, 17.4
	θ_e, 1 293	L_e, 160.4
$PbCl_2$	θ_m, 498	L_m, 24.3
	θ_e, 954	L_e, 123.9
$PbBr_2$	θ_m, 370	L_m, 18.0
	θ_e, 914	L_e, 116.0
PbI_2	θ_m, 410	L_m, 16.2
	θ_e, 872	L_e, 103.8
$PdCl_2$	θ_m, 678	L_m, 18.4
$PrCl_3$	θ_m, 786	L_m, 50.7
$PrBr_3$	θ_m, 693	L_m, 47.3
PrI_3	θ_m, 735	L_m, 53.2
PuF_3	θ_m, 1 426	L_m, (59.9)
	θ_e, (2120)	L_m, (321)
PuF_6	θ_m, 52	L_m, 17.6
	θ_s, 62	L_e, 30.1
$PuCl_3$	θ_m, 760	L_m, 63.6
	θ_e, 1 790	L_e, 186
$PuBr_3$	θ_m, 681	L_m, 51.5
	θ_e, 1 460	L_e, 193
RbF	θ_m, 775	L_m, 23.0
	θ_e, 1 390	L_e, 177.9
RbCl	θ_m, 717	L_m, (21)
	θ_e, 1 381	L_e, 165.8
RbBr	θ_m, 682	L_m, (18.4)
	θ_e, 1 352	L_e, 154.9
RbI	θ_m, 641	—
	θ_e, 1 304	L_e, 150.7
ReF_5	θ_e, 221	L_e, 58.2
ReF_6	θ_m, 19	L_m, 4.2
	θ_e, 34	L_e, 28.5
ReF_7	θ_e, 48	L_m, 7.5
	θ_e, 74	L_e, 36.0
SF_6	θ_m, −51	L_m, 5.9
	θ_s, −64	—
S_2Cl_2	θ_m, −80	—
	θ_e, 138	L_e, 36.4
$SbCl_3$	θ_m, 73	L_m, 12.6
	θ_e, 219	L_e, 43.5
$SbCl_5$	θ_m, 2	L_m, (10.5)
$SbBr_3$	θ_m, 97	L_m, 14.7
	θ_e, 280	L_e, (59.0)
SbI_3	θ_m, 170	L_m, 17.6
	θ_e, 401	L_e, 68.7
$ScCl_3$	θ_m, 966	L_m, 67.4
	θ_e, 967	L_s, 272.1
SeF_6	θ_m, −34	L_m, (8.4)
	θ_s, −46	L_s, 26.8
SiF_4	θ_s, −95	L_s, 25.8
$SiCl_4$	θ_m, −70	L_m, 7.75
	θ_e, 57	L_e, 28.9
$SiBr_4$	θ_e, 153	L_e, 38.1
SiI_4	θ_e, 301	L_e, 50.2
$SnCl_2$	θ_m, 247	L_m, 12.77
	θ_e, 652	L_e, 82.9
$SnCl_4$	θ_m, −33	L_m, 9.2
	θ_e, 115	L_e, 33.9
$SnBr_2$	θ_m, 232	L_e, 98.4
	θ_e, 639	L_m, (7.5)

Table 8.3 OTHER METALLURGICALLY IMPORTANT COMPOUNDS—*continued*

Compound	θ_m, θ_e, θ_s or θ_t °C	L_m, L_e, L_s or L_t kJ mol^{-1}
Halides—continued		
$SnBr_4$	θ_m, 30	L_m, 12.6
	θ_e, 205	L_e, 41.0
SnI_2	θ_m, 320	—
	θ_m, 714	L_e, 99.6
SnI_4	θ_s, 145	L_m, 19.3
	θ_e, 348	L_e, 50.2
SrF_2	θ_m, 1 477	L_m, 18.4
	θ_e, 2 480	L_e, 297.2
$SrCl_2$	θ_m, 874	L_m, 15.9
$SrCl_2$	θ_t, 730	L_t, 5.0
$SrBr_2$	θ_m, 657	L_m, 10.5
	θ_t, 645	L_t, 12.1
SrI_2	θ_m, 538	L_m, 19.7
$TaCl_5$	θ_m, 217	L_m, 36.8
	θ_e, 234	L_e, 50.2
$TaBr_5$	θ_m, 269	L_m, 45.6
	θ_e, 347	L_e, 62.4
TaI_5	θ_m, 497	—
	θ_e, 543	L_e, 75.8
TeF_6	θ_m, 130	L_m, 26.8
$TeCl_2$	θ_e, 322	L_e, 64.1
$TeCl_4$	θ_m, 224	L_m, 18.8
	θ_e, 392	L_e, 70.3
$ThCl_4$	θ_m, 770	—
	θ_e, 921	L_e, 152.8
$ThBr_4$	θ_m, 679	L_m, 54.4
	θ_e, 857	L_e, 144.4
ThI_4	θ_m, 566	L_m, 48.1
	θ_e, 837	L_e, 131.9
TiF_4	θ_s, 283	L_s, 90.0
$TiCl_4$	θ_m, −25	L_m, 9.37
	θ_e, 136	L_e, 36.22
$TiBr_4$	θ_m, 39	L_m, 13.0
	θ_e, 233	L_e, 44.4
TiI_2	θ_s, 1 170	L_s, 222.7
TiI_4	θ_m, 154	L_m, 19.8
	θ_e, 377	L_e, 56.1
TlF	θ_e, 700	L_e, 116.0
TlCl	θ_m, 430	L_m, 15.9
	θ_e, 816	L_e, 103.6
TlBr	θ_m, 460	L_m, 16.3
	θ_e, 825	L_e, 103.4
TlI	θ_e, 845	L_e, 103.8
	θ_m, 440	L_m, 14.8
UF_4	θ_m, 1 036	L_m, 42.7
	θ_e, 1 457	L_e, 221.9
UF_6	θ_m, 64	L_m, 19.3
	θ_s, 57	L_s, 48.1
UCl_4	θ_m, 590	L_m, 44.8
	θ_e, 789	L_e, 141.5
UBr_4	θ_m, 519	L_m, 55.3
	θ_e, 777	L_e, 113.5
VF_5	θ_e, 48.3	L_e, 46.5
VCl_4	θ_e, 160	L_e, 33.1
WF_6	θ_m, 0	L_m, 1.76
	θ_e, 17	L_e, 26.6
WCl_5	θ_e, 298	L_e, 52.8
	θ_m, 240	L_m, (17.6)
WCl_6	θ_m, 282	L_m, 6.7
	θ_e, 337	L_e, 58.2
ZnF_2	θ_m, 875	L_m, 41.8
	θ_e, 1 500	L_e, 184.2
$ZnCl_2$	θ_m, 318	L_m, 10.5
	θ_e, 732	L_e, 119.3
$ZnBr_2$	θ_m, 402	L_m, 15.7
	θ_e, 650	L_e, 98.4
ZnI_2	θ_m, 446	L_m, (18.8)
	θ_e, 727	L_e, 96
ZrF_4	θ_s, 908	L_s, 232.4
$ZrCl_4$	θ_s, 334	L_s, 103.8
$ZrBr_4$	θ_s, 356	L_s, 108.0
ZrI_4	θ_s, 431	L_s, 121.4
Nitrides		
Mg_3N_2	θ_t, 550	L_t, 0.46
	θ_t, 788	L_t, 0.92
Oxides		
As_4O_6	θ_t, −33	L_t, 5.7
	θ_m, 309	L_m, 36.8
	θ_e, 459	L_e, 59.9
BeO	θ_m, 2 580	80.8
	θ_e, 4 120	L_e, 471.0
CdO	θ_s, 1 559	L_s, 251
$Fe_{0.95}O$	θ_m, 1 378	L_m, 31.0
Fe_3O_4	θ_m, 1 597	L_m, 138.2
H_2O	θ_m, 0	L_m, 6.016
	θ_e, 100	L_e, 41.11
MgO	θ_m, 2 825	L_m, 77.0
MnO	θ_m, 1 875	L_m, 54
Mn_3O_4	θ_t, 1 172	L_t, 20.3
MoO_3	θ_m, 795	L_m, 48.4
	θ_e, 1 100	L_e, 192.6
NbO_2	θ_t, 817	L_t, 2.9
OsO_4 (white)	θ_m, 42	L_m, 9.6
	θ_e, 130	L_e, 39.57
P_4O_6	θ_e, 175	L_e, 43.5
PbO (yellow)	θ_m, 886	L_m, 29.3
	θ_e, 1 470	L_e, (214.8)
Re_2O_7	θ_m, 298	L_m, 64.1
	θ_e, 363	L_e, 75.4
SO_2	θ_m, −75.5	L_m, 7.5
	θ_e, −10	L_e, 24.95
SO_3	θ_m, 17 (α)	L_m, 2.1
	θ_s, 52 (γ)	L_s, 66.6
Sb_4O_6	θ_t, 570	L_t, (14.2)
	θ_m, 656	L_m, 109.9
	θ_e, 1 425	L_s, 214.4 (m.p.)
SeO_2	θ_s, 316	L_s, (102.6)
SiO_2	θ_t, 250	L_t, 1.3
(cristobalite)	θ_m, 1 713	L_m, 10.9
SnO_2	θ_t, 410	L_t, 1.88
	θ_t, 540	L_t, 1.26
SrO	θ_m, 2 460	L_s, 523 (25 °C)
Tc_2O_7	θ_m, 119	L_m, 48.1
	θ_e, 312	L_e, 58.6
TeO_2	θ_m, 733	L_s, 237.8 (m.p.)
TiO	θ_t, 991	L_t, 3.43
Ti_3O_5	θ_t, 177	L_t, 9.38
VO_2	θ_m, 1 550	L_m, 56.9
	θ_t, 67	L_t, 4.29
V_2O_5	θ_m, 670	L_m, 65.3
WO_3	θ_m, 1 473	L_s, 456 (m.p.)
ZrO_2	θ_t, 1 175	L_t, 5.9
Sulphides		
Ag_2S	θ_t, 176; 586	L_t, 5.9; —
	θ_m, 830	L_m, 11.3

Table 8.3 OTHER METALLURGICALLY IMPORTANT COMPOUNDS—*continued*

Compound	θ_m, θ_e, θ_s or θ_t °C	L_m, L_e, L_s or L_t kJ mol^{-1}	*Compound*	θ_m, θ_e, θ_s or θ_t °C	L_m, L_e, L_s or L_t kJ mol^{-1}
	Sulphides—continued			*Sulphides*—continued	
CS_2	θ_e, 45.2	L_e, 27.2	HgS	θ_t, 345	L_t, 4.2
Cu_2S	θ_t, 103	L_t, 3.85	H_2S	θ_m, −85.3	L_m, 2.43
	θ_t, 350	L_t, 0.8		θ_e, −60.2	L_e, 18,686
	θ_m, 1 130	L_m, 10.9	MnS	θ_m, 1 530	L_m, 26.8
FeS	θ_t, 138	L_t, 2.39			
	θ_t, 325	L_t, 0.50	Na_2S	θ_m, 978	L_m, (6.91)
	θ_m, 1 195	L_m, 32.36	Sb_4S_6	θ_m, 550	L_m, 126.3 (25 °C)
GeS	θ_m, 615	L_m, 21.4		—	L_σ 214.4 (m.p.)
	θ_s, 760	L_s, 145.3	ZnS	θ_t, 1 020	L_t, (13.4)

8.3 Heat, entropy and free energy of formation

Table 8.4 ELEMENTS
Standard entropies

Element	S_{298} J K^{-1}	*Element*	S_{298} J K^{-1}	*Element*	S_{298} J K^{-1}
Ag	42.7	Hf	44.0	Rh	31.8
Al	28.34	Hg	76.20	Ru	28.5
As	35.2	I	58.6	S (rhomb.)	31.90
Au	47.39	In	58.2		
B (cryst.)	5.9			S (monocl.)	32.57
		Ir	35.6	S_2 (gas)	227.8
Ba	(67.8)	K	63.6	S_4 (gas)	306.1
Be	9.50	La	56.9	S_6 (gas)	376.0
Bi	56.9	Li	29.1	S_8 (gas)	471.4
Br_2 (liq.)	152.4	Mg	32.5		
C (graph.)	5.69			Sb	45.6
		Mn	31.82	Sc	34.3
Ca	41.66	Mo	28.6	Se (met.)	42.3
Cd	51.5	N_2	191.63	Si	18.8
Ce	64.1	Na	51.29	Sm	69.5
Cl_2	223.24	Nb	36.55		
Co	30.06			Sn	51.5
		Nd	73.3	Ta	41.4
Cr	23.9	Ni	29.81	Te	49.61
Cs	82.9	O_2	205.24	Th	53.42
Cu	33.37	Os	32.7	Ti	30.31
Dy	74.9	P (yellow)	44.17		
Er	73.3			Tl	64.27
		Pb	64.9	U	50.2
F_2	203.1	Pd	37.89	V	29.3
Fe	27.2	Pr	73.3	W	33.5
Ga	41.0	Pt	41.9	Y	44.4
Gd	66.2	Pu	51.5		
Ge	31.19			Zn	41.7
		Rb	76.6	Zr	38.9
H_2	130.75	Re	37.3		

Table 8.5a INTERMETALLIC COMPOUNDS
Heats of formation in kJ and standard entropies

Phase or compound	$-\Delta H$ kJ g-atom^{-1}	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1} mol^{-1}
Ag–Au	*See* Table 8.5c		—
Ag–Cd	*See* Table 8.5c		—
Ag–Zn	*See* Table 8.5c		—
Al_2Au (α)	42.1	126.4	—
AlAu (β)	38.7	77.4	—
$AlAu_2$ (γ)	34.9	104.7	—
Al_4Ca	—	218.5	138.1
Al_2Ca	—	216.8	85.4
Al_4Co (γ)	32.2	—	—
Al_5Co_2 (ε)	42.0	—	—
AlCo (ξ)	55.2	—	—
Al_7Cr (θ)	13.4	—	—
$Al_{11}Cr_2$ (η)	15.1	—	—
Al_4Cr (ε)	17.2	—	—
Al_9Cr_4 (γ_4)	15.9	—	—
Al_8Cr_5 (γ_2)	15.1	—	—
$AlCr_2$ (β)	10.9	—	—
Al_2Cu (θ)	13.4	—	—
AlCu (η_2)	20.0	—	—
$AlCu_2$ (γ)	23.0	—	—
Al-Fe	*See* Table 8.5c		—
Al_4La (β')	35.2	—	—
Al_2La	—	150.7	98.8
AlAs	—	122.6	60.3
AlSb	—	50.2	65.0
Al_3Ni (ε)	37.7	150.7	110.7
Al_3Ni_2 (δ)	56.5	282.6	136.5
AlNi (β)	59.2	118.5	54.1
$AlNi_3$ (α')	37.7	150.8	113.8
Al_4Pu	36.2	181.0	—
Al_3Pu	45.2	180.8	—
Al_2Pu	47.3	141.9	—
Al_3Ti (γ)	35.6	142.3	94.6
AlTi (δ)	37.0	—	52.3
$AlTi_3$ (ε)	27.6	—	—
Al_4U	26.0	129.7	163.3
Al_3U	28.6	114.3	136.0
Al_2U	32.9	98.8	106.7
Al_3V (ξ)	27.6	—	—
AsIn	—	57.8	74.7
An–Cd	*See* Table 8.5c		—
Au–Cu	*See* Table 8.5c		—
Au–Ni	*See* Table 8.5c		—
Au–Pb	*See* Table 8.5c		—
$AuSb_2$	—	19.5	119.3
AuSn	*See* Table 8.5c		—
Au_3Zn (α)	(18.0)	—	—
AuZn (β)	(26.0)	—	—
Ba_3Bi_2	—	670	—
$BaMg_2$ (β)	2.1	6.3	—
Ba_2Pb	97.6	293.0	—
BaPb	75.0	150.0	—

Table 8.5a INTERMETALLIC COMPOUNDS—*continued*

Phase or compound	$-\Delta H$ kJ g-atom^{-1}	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1} mol^{-1}
$BaPb_3$	44.0	176.0	—
Ba_3Sb_2	146.5	733	—
Ba_2Sn	—	377.0	126.8
$BaSn_3$	—	194.6	188.0
Bi_2Ca_3	—	528.0	117.9
BiK_3	—	226.5	198.0
BiMn	9.8	19.7	—
BiNa	32.7	65.3	109.6
$BiNa_3$	47.6	190.5	160.0
BiNi	3.9	7.8	88.3
Bi–Tl	*See* Table 8.5c		—
$CaCd_3$	31.4	126.0	—
$CaMg_2$	—	39.3	—
Ca_2Pb	—	215.6	105.5
CaPb	—	119.7	80.8
Ca_3Sb_2	—	728.4	157.4
Ca_2Su	—	314	100.5
CaSn	—	159.0	70.7
$CaSn_3$	—	180.0	—
CaTl	81.6	163.2	—
CaZn (δ)	36.6	73.2	66.6
$CaZn_2$	31.4	94.2	101.7
$CaZn_5$ (ξ)	23.0	138.1	—
Cd–Hg	*See* Table 8.5c		—
Cd–Mg	*See* Table 8.5c		—
Cd–Sb	*See* Table 8.5c		—
Cd_3As_2	—	38.1	207.2
Cd_6Na (β)	7.5	—	—
Cd_2Na (γ)	11.7	—	—
CeMg (β)	8.0	—	—
Co_5As_2	—	111.3	223.1
Co_2As	18.8	56.5	96.3
Co_3As_2	—	113.8	160.3
CoAs	—	56.9	64.5
Co_2As_3	—	144.0	164.1
$CoAs_2$	—	92.1	92.9
CoSb (γ)	20.9	41.8	70.7
$CoSb_x$($x = 0.74 \rightarrow 0.96$)			
CoSn	14.7	29.3	71.6
Cr–Ni	*See* Table 8.5c		—
Cr_2Ta	9.0	27.0	88.1
Cu_7In_3 (δ)	8.5	—	—
Cu_2In (η)	8.0	—	—
Cu–Mg	*See* Table 8.5c		—
Cu–Pt	*See* Table 8.5c		—
$Cu_{11}Sb_2$ (η)	0.26	—	—
Cu_9Sb_2 (ϵ)	0.54	—	—
Cu_2Sb (γ)	4.2	—	—
$Cu_{31}Sn_8$(δ)	5.36	—	—
Cu_3Sn(ε)	7.5	--	—
Fe–Ni	*See* Table 8.5c		—
Fe_2Pu(ζ)	9.1	27.3	—
$FeSb_2$(ζ)	(9.6)	—	—
FeTi(ε)	20.3	40.6	—

Table 8.5a INTERMETALLIC COMPOUNDS—*continued*

Phase or compound	$-\Delta H$ kJ g-atom^{-1}	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1} mol^{-1}
$Fe_2U(\varepsilon)$	10.9	32.2	—
GaAs	—	81.6	64.2
GaSb	—	41.9	77.4
GeU	*See* Table 8.5c		—
Hg_8K	11.6	104.6	—
Hg_4K	18.0	90.0	—
Hg_3K	20.9	83.6	—
Hg_2K	38.7	77.4	—
HgK	28.1	56.1	—
Hg_3Li	28.2	113.0	—
Hg_2Li	34.8	104.4	—
HgLi	44.0	88.0	—
Hg_4Na	16.7	83.5	—
HgNa	21.4	42.7	—
Hg_2Na_3	18.8	94.4	—
Hg_2Na_5	13.4	93.8	—
$HgNa_3$	11.7	46.9	—
Hg_5Tl_2	*See* Table 8.5c		—
InSb	—	31.1	87.7
KNa_2	*See* Table 8.5c		—
K_3Bi	56.6	226.4	—
K_3Sb	47.1	188.4	—
KTl	28.3	56.5	—
$LaMg(\zeta)$	9.0	18.0	—
$Li_4Pb(\gamma)$	35.2	—	—
$LiPb(\zeta)$	30.6	—	—
Li_3Bi	—	232.3	—
Li_3Sb	—	180.0	—
LiTl	—	153.6	—
βLi–Sn	39.3	—	—
$Li_5Sn_2(\delta)$	40.2	—	—
$LiSn(\zeta)$	35.1	—	—
Mg_2Ge	—	115.2	73.0
Mg_2Sn	—	80.6	101.5
Mg_2Pb	—	48.1	119.3
Mg_3Sb_2	—	300.1	136.7
Mg_3Bi_2	25.3	126.8	191.9
Mg_2Ni	17.3	51.9	95.0
$MgNi_2$	18.8	56.5	88.7
$MgZn(\gamma)$	10.5	—	—
$MgZn_2(\varepsilon)$	10.9	—	—
$Mg_2Zn_{11}(\zeta)$	10.0	—	—
MnAs	—	57.3	—
Mn_2Sb	—	32.6	136.9
Na_3As	—	217.7	—
Na_3Sb	—	197.6	176.2
NaSb	—	66.2	99.8
Na_3Bi	—	190.5	(160)
NaBi	—	65.3	(110)
Na_4Sn	11.7	58.6	—
Na_2Sn	20.1	60.3	—
NaSn	25.1	50.2	—
Na–Pb	*See* Table 8.5c		—

Table 8.5a INTERMETALLIC COMPOUNDS—*continued*

Phase or compound	$-\Delta H$ kJ g-atom^{-1}	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1} mol^{-1}
NaTl	*See* Table 8.5c		—
$NbCr_2$	—	20.9	83.7
$NbFe_2$	—	61.5	75.3
NbNi(γ)	22.6	—	—
$NbNi_3$(δ)	31.8	—	—
Ni_2Ge	—	110.1	90.8
NiAs	—	72.0	51.9
Ni_3Sb(δ)	18.8	—	—
Ni_5Sb_2(β')	21.8	—	—
NiSb(γ)	33.1	66.2	78.3
$NiSb_2$(ε)	24.7	—	—
Ni_3Sn (β')	25.2	103.0	131.4
Ni_3Sn_2(γ)	38.5	192.3	173.7
Ni_3Sn_4 (δ)	33.7	235.7	257.9
Ni_3Ti	35.1	140.3	104.6
NiTi	33.3	66.6	53.2
$NiTi_2$	27.9	83.7	83.6
Pb–Tl	*See* Table 8.5c		—
Pb–U	*See* Table 8.5c		—
Sb–Zn	*See* Table 8.5c		—
$TaFe_2$	—	57.8	106.7
$ThRe_2$	—	174.1	123.7
$ThMg_2$	—	31.4	92.5
UCd_{11}	—	45.6	583.5
UFe_2	—	32.2	104.7
URh_3	—	259.5	148.2
URu_3	—	217.6	108.4

Table 8.5b SELENIDES AND TELLURIDES

Heats of formation in kJ and standard entropies

Compound	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1}	*Accuracy* kJ
Ag_2Se	43.5	150.3	1
Ag_2Te	36.0	153.6	0.5
Al_2Se_3	540.0	157.0	15
Al_2Te_3	319.0	188.4	4
As_2Se_3	102.6	194.6	18
As_2Te_3	37.7	226.5	7
$AuTe_2$	18.6	141.8	3
BaSe	393.5	89.6	40

Table 8.5b SELENIDES AND TELLURIDES—*continued*

Compound	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1}	*Accuracy* kJ
BaTe	269.6	99.6	30
Bi_2Se_3	140.2	240.0	4
Bi_2Te	78.3	261.2	4
CaSe	368.4	69.1	25
CaTe	272.1	80.8	33
CdSe	144.8	83.3	14
CdTe	101.8	93.1	1
Cu_2Se	65.3	129.8	7
CuSe	41.9	78.3	5
Cu_2Te	41.9	134.8	11
$FeSe_{0.96}$	67.0	69.2	7
$FeSe_{1.14}$	66.1	87.7	4
Fe_3Se_4	212.2	280.0	3
$FeTe_{0.9}$	23.0	80.2	4
$FeTe_2$	72.0	100.3	5
GaSe	161.2	70.3	11
Ga_2Se_3	406.0	192.1	17
GaTe	123.5	85.4	11
Ga_2Te_3	272.1	222.7	13
GeSe	69.1	87.5	13
$GeSe_2$	113.0	112.6	21
GeTe	32.7	89.2	13
$H_2Se_{(g)}$	−29.3	218.9	1.3
$H_2Te_{(g)}$	−99.6	229.0	0.9
HgSe	43.3	100.9	15
HgTe	31.8	113.0	4.5
InSe	118.0	81.6	13
In_2Se_2	326.5	201.3	17
In_2Te	79.5	157.0	2
InTe	72.0	105.7	2
In_2Te_3	191.7	238.6	3
In_2Te_5	191.7	—	2.5
K_2Se	372.6	—	2.5
La_2Se_3	933.5	202.3	21
La_2Te_3	784.9	223.4	25
Li_2Se	401.8	71.2	40
Li_2Te	355.8	77.4	—
MgSe	272.9	62.8	17
MgTe	209.3	74.5	21
MnSe	154.9	90.8	11
MnTe	111.3	93.8	9
$MnTe_2$	125.6	145.0	40
Na_2Se	343.2	—	13
NaSe	194.2	62.8	21
Na_2Te	343.2	94.6	25
NaTe	173.3	83.7	11
$NaTe_3$	210.6	145.3	21
$NiSe_{1.05}$	74.9	75.2	4
$NiSe_{1.143}$	79.7	77.2	2.5
NiTe	35.7	80.1	2
PbSe	99.6	102.6	4
PbTe	69.1	110.1	1

Table 8.5b SELENIDES AND TELLURIDES—*continued*

Compound	$-\Delta H$ kJ mol^{-1}	S_{298} J K^{-1}	*Accuracy* kJ
Pt_3Se_4	265.4	327.3	25
Re_2Te_5	122.6	253.3	25
Sb_2Se_3	127.7	211.4	5
Sb_2Te_3	56.5	246.1	2
$SiSe_2$	146.5	94.2	40
SnSe	88.7	86.2	7
$SnSe_2$	124.7	118.0	5
SnTe	60.7	98.8	1.5
SrTe	397.7	80.8	38
SrTe	259.5	—	25
Tl_2Se	94.2	173.7	2.5
TlSe	61.3	102.6	1.5
Tl_2Te	80.4	174.1	12
USe	275.9	96.6	21
ZnSe	159.1	70.3	9
ZnTe	119.3	78.2	1

The above values of the heat of formation ΔH were measured calorimetrically at room temperature or at about 600 °C, or have been calculated from measurements of vapour pressure or electromotive force at different temperatures. They are probably correct to within $\pm 10\%$. As the molar heats of alloys are obtained nearly additively from the atomic heats of the components (Neumann and Kopp's rule) all the heats of formation (even if measured at higher temperatures) are probably valid also at room temperature within the limits of error mentioned above. The formulae of the compounds are given only to indicate composition, independent of whether the phases form a broad or narrow homogeneous field, or are ordered or disordered.

Table 8.5c INTERMETALLIC PHASES
Heats, entropies and free energies of formation

Phase	N_2	*Temp.* °C	$-\Delta H$ kJ g-atom^{-1}	$-\Delta G$ kJ g-atom^{-1}	ΔS J K^{-1} g-atom^{-1}	*Remarks*
Ag–Au, s.s.	0.55	600	4.02	8.08	5.02	
α Ag–Cd	0.40	400	7.16	—	4.15	
ζ Ag–Cd	0.564	400	6.78	—	4.52	
β Ag–Cd	0.494	450	6.62	—	—	
γ′ Ag–Cd	0.60	400	8.37	—	1.88	Cd solid
ε Ag–Cd	0.70	400	6.45	—	2.85	
AgMg	0.50	500	19.47	17.08	1.38	
Ag–Pd, s.s.	0.40	727	5.65	—	−2.09	
β Ag–Zn	0.50	600	3.14	10.34	8.25	Zn solid
ζ Ag–Zn	0.50	51	6.45	—	—	
γ Ag–Zn	0.612	600	4.48	10.09	6.41	Zn solid
θ Al–Fe	0.26	900	28.1	—	−3.94	
η Al–Fe	0.30	900	28.26	—	−3.56	Al solid
ζ Al–Fe	0.33	900	27.2	—	−2.34	
AlFe	0.50	900	27.2	—	0.13	
α Al–Zn	0.20	380	−4.02	—	7.45	
α Au–Cd	0.35	427	17.38	15.78	−2.26	
β Au–Cd	0.50	427	21.35	18.42	−4.19	Cd liquid
δ′ Au–Cd	0.62	427	19.05	16.20	−3.48	
ε Au–Cd	0.70	427	19.26	15.83	−4.90	

ΔS = entropy of formation. N_2 = mol fraction of second component. s.s. = solid solution.

Table 8.5c INTERMETALLIC PHASES—*continued*

Phase	N_2	*Temp.* °C	$-\Delta H$ kJ g-atom^{-1}	$-\Delta G$ kJ g-atom^{-1}	ΔS J K^{-1} g-atom^{-1}	*Remarks*
Au–Cu, s.s.	0.58	500	5.32	9.67	5.65	
Au_3Cu	0.26	25	4.02	4.90	2.97	
AuCu I	0.50	25	8.96	8.96	0.00	
Au Cu II	0.50	400	6.03	8.79	4.10	
$AuCu_3$	0.75	25	6.87	7.24	1.26	
AuNi, s.s.	0.53	877	−7.5	—	8.71	
Au_2Pb	0.33	227	−0.96	1.34	4.61	
$AuPb_2$	0.67	227	2.09	1.80	−0.72	
AuSn	0.50	25	15.24	—	−0.23	
Bi–Tl, δ	0.47	150	2.81	5.28	5.86	
Bi–Tl, γ	0.80	150	3.18	5.15	4.69	
Bi_2U	0.333	25	34.2	—	−3.93	
Bi_4U_3	0.43	25	38.1	—	−5.0	
BiU	0.50	25	36.8	—	−4.96	
β Cd–Hg	0.50	25	4.35	4.06	−0.92	Hg liquid
Cd–Mg, s.s.	0.50	270	5.61	7.96	4.35	
Cd_3Mg	0.25	25	5.19	5.19	−0.04	
CdMg	0.50	25	8.37	8.08	−1.05	
$CdMg_3$	0.75	25	5.65	5.61	−0.17	
CdSb	0.50	25	6.67	6.42	−0.86	
CdTe	0.50	20	50.9	49.7	−4.12	
$CeHg_4$	0.80	342	66.6	7.54	−96.13	Hg gas
α Co–Fe, s.s.	0.50	870	6.6	—	—	
α Cr–Fe, s.s.	0.50	1 280	−5.9	−7.63	8.42	
σ Cr–Fe	0.55	750	−4.73	—	6.91	
Cr–Mo, s.s.	0.47	1 400	−7.24	—	7.70	
Cr–Ni, f.c.c.	0.50	1 265	−6.70	—	9.21	
Cu_2Mg	0.333	25	11.18	—	−8.4	
$CuMg_2$	0.667	25	9.6	—	—	
Cu–Ni, s.s.	0.65	700	−1.84	—	4.40	
Cu–Pd, s.s.	0.40	640	12.6	—	−5.32	
Cu–Pt, s.s.	0.50	640	15.5	—	−4.15	
Cu_2Sb	0.33	25	4.2	—	−3.56	
α Cu–Zn	0.39	25	9.38	10.22	2.81	
β Cu–Zn	0.50	—	9.17	—	4.19	
β' Cu–Zn	0.50	25	11.72	12.14	1.47	
γ Cu–Zn	0.615	—	12.35	—	0.54	
ε Cu–Zn	0.79	25	7.20	7.49	1.00	
γ Fe–Mn	0.5	1 127	5.0	—	—	
γ Fe–Ni, s.s.	0.65	1 000	4.35	—	3.60	
$FeSb_2$	0.67	560	3.4	—	−0.8	
Ge_3U	0.25	1 100	26.8	—	−1.47	
Ge_2U	0.33	1 100	29.3	—	−1.3	
Ge_5U_3	0.375	1 100	30.2	—	−1.3	
GeU	0.50	1 100	30.77	—	−1.09	
Ge_3U_5	0.625	1 050	29.48	—	−0.38	
γ Hg–Tl	0.286	−59	−0.29	1.05	6.45	
β In–Sn	0.42	100	−2.1	—	—	
KNa_2	0.667	25	−0.75	0.63	4.61	Na_2K, Na, K; liquid
	0.667	25	−0.04	0.29	1.13	Na_2K, Na, K: solid
Na_5Pb_2	0.286	25	20.5	—	−6.7	

ΔS = entropy of formation. N_2 = mol fraction of second component. s.s. = solid solution.

Table 8.5c INTERMETALLIC PHASES—*continued*

Phase	N_2	*Temp.* °C	$-\Delta H$ kJ g-atom^{-1}	$-\Delta G$ kJ g-atom^{-1}	ΔS J K^{-1} g-atom^{-1}	*Remarks*
Na_9Pb_4	0.31	25	20.9	—	−6.3	
NaPb	0.50	25	23.0	—	−8.8	
$NaPb_3$	0.714	25	13.8	—	−2.1	
NaTl	0.50	25	16.54	–	−3.98	
α Pb–Tl	0.50	250	1.80	4.19	4.56	
β-Pb–Tl	0.85	270	2.81	2.81	0.0	
Pb_3U	0.25	700	19.7	- -	−0.4	Pb solid
PbU	0.50	700	18.8	—	−1.3	
SbZn	0.50	25	9.52	8.85	−2.26	
Sn_3U	0.25	950	23.9	—	−0.63	Sn solid
Sn_5U_3	0.375	950	27.2	—	−1.17	
Sn_2U_3	0.60	1000	26.8	—	−1.05	
Th_2Zn	0.333	700	22.2	15.5	−7.75	
$ThZn_2$	0.667	700	40.2	25.5	−15.1	
$ThZn_4$	0.80	700	38.5	23.0	−15.1	
Th_2Zn_{17}	0.895	700	32.7	13.0	−16.96	
U_2Zn_{17}	0.895	700	24.3	7.5	−17.2	
ZrZn	0.50	500	63.6	32.2	−40.6	
$ZrZn_2$	0.667	500	56.1	30.1	−33.5	
$ZrZn_3$	0.75	500	54.22	28.5	−33.29	
$ZrZn_6$	0.86	500	40.6	18.8	−28.26	
$ZrZn_{14}$	0.933	500	28.1	9.42	−24.07	

ΔS = entropy of formation. N_2 = mol fraction of second component. s.s. = solid solution.

8.4 Metallic systems of unlimited mutual solubility

While mutual solubility in the solid state is usually limited, that in the liquid state is frequently unlimited. Thus, the curves of concentration against integral heat, free energy and entropy of formation are convex with a maximum or a minimum. The thermochemical values at the concentrations corresponding to these maxima and minima are given in Table 8.6.

According to van Laar the form of the heat of mixing curve may be represented by

$$\Delta H = \frac{aN_2(1-N_2)}{1+b \cdot N_2}$$

where N_2 is the mol fraction of the second component and a and b are constants for each binary system.

For a system, completely disordered, the entropy of formation is often represented by this equation:

$$\Delta S = -19.155\,(N_1 \log N_1 + N_2 \log N_2) \qquad \text{J K}^{-1}\text{ g-atom}^{-1}$$

which has a maximum value of 5.78 J K^{-1} g-atom^{-1} at $N_1 = N_2 = 0.5$. Some deviations from this value may be due to experimental errors, but others are real.

For more detailed discussions *see* refs 1–3.

Table 8.6 LIQUID BINARY METALLIC SYSTEMS
Heats and entropies of formation

		Heat of formation		*Entropy of formation*	
System	°C	N_2	ΔH_{max} J g-atom^{-1}	N_2	ΔS_{max} J K^{-1} g-atom^{-1}
Ag–Al	1 000	0.30	−6 410	0.60	7.58
Ag–Au	1 077	0.50	−5 150	0.50	3.81
Ag–Bi	727*	0.75	1 700	0.50	6.17
Ag–Cu	1 150	0.45	4 260	0.50	6.27
Ag–In	827*	0.32	−5 680	0.70	3.82
Ag–Mg	1 050	0.50	1 215	—	—
Ag–Pb	1 000	0.53	3 720	0.47	7.62
Ag–Sb	977	0.20	−3 120	0.52	8.37
Ag–Sn	977	0.19	−3 220	0.56	6.68
Ag–Tl	702*	0.56	2 510	0.50	6.32
Al–Bi	900	0.40	7 340	—	—
Al–Cu	1 100	0.60	−9 435	0.60	9.25
Al–Ga	750	0.40	670	0.50	6.10
Al–Ge	927	0.53	−3 915	0.50	6.20
Al–In	900	0.45	5 735	0.50	6.36
Al–Mg	800	0.45	−3 390	0.50	4.94
Al–Sn	700	0.45	4 100	0.50	6.99
Al–Zn	727	0.51	2 575	0.50	6.71
Au–Bi	700*	0.50	625	0.50	6.97
Au–Cu	1 277	0.53	−4 400	0.53	6.90
Au–Pb	927*	0.40 0.90	−795 260	0.50	7.54
Au–Sn	550*	0.45	−11 595	0.42	7.91
Au–Tl	700*	0.50	140	0.50	7.86
Au–Zn	807*	0.52	−22 810	0.25	4.50
Bi–Cd	500	0.65	880	0.52	7.25
Bi–Cu	927†	0.60	5 420	0.50	7.59
Bi–Hg	321	0.70	555	0.50	5.55
Bi–In	627	0.55	−185	0.50	5.87
Bi–Pb	427	0.50	−1 100	0.50	5.94
Bi–Sb	927	0.50	560	0.50	8.15
Bi–Sn	327	0.50	105	0.50	5.48
Bi–Tl	477	0.62	−4 580	0.50	6.67
Bi–Zn	600	0.58	4 685	0.50	7.85
Cd–Ga	427	0.50	2 665	0.50	5.73
Cd–Hg	327	0.50	−2 625	0.43	5.28
Cd–In	527	0.46	1 435	0.50	6.32
Cd–Mg	650	0.50	−5 615	0.50	4.72
Cd–Pb	500	0.45	2 665	0.45	6.50
Cd–Sb	500†	0.47	−2 035	0.50	6.92
Cd–Sn	500	0.43	1 815	0.50	6.91
Cd–Tl	477	0.40	2 300	0.50	6.78
Cd–Zn	527	0.50	2 090	0.50	5.86
Co–Fe	1 590	0.45	−2 610	0.58	3.80
Cs–K	111	0.59	126	—	—
Cs–Na	111	0.65	1 020		
Cu–In	800*	0.23 0.82	−3 390 305	0.55	4.83
Cu–Mg	827*	0.44	10 445	0.50	2.53
Cu–Pb	1 200	0.45	6 800	0.49	6.85
Cu–Sb	917*	0.25 0.90	−5 660 345	0.55	8.20

N_2 = mol fraction of second component.
* or † indicates that the standard state for the first or second component, respectively, is the hypothetical supercooled liquid.

Table 8.6 LIQUID BINARY METALLIC SYSTEMS—*continued*

		Heat of formation		*Entropy of formation*	
System	°C	N_2	ΔH_{max} J g-atom^{-1}	N_2	ΔS_{max} J K^{-1} g-atom^{-1}
Cu–Sn	1 127	0.25 0.90	−4 150 218	0.54	8.16
Cu–Tl	1 300	0.50	8 580	0.52	7.75
Fe–Si	1 600	0.48	−37 950	0.05 0.54 0.95	1.05 −1.66 0.65
Ga–Zn	477	0.58	1 610	0.50	6.80
Hg–In	25†	0.48	−2 260	0.45	5.25
Hg–Na	400	0.40	−20 570	(0.04) 0.39 0.12	(0.4) −4.57 0.71
Hg–Pb	327	0.20 0.83	505 −160	0.50	4.60
Hg–Sn	177†	0.40	905	0.50	5.17
Hg–Tl	310	0.28	−1 130	—	—
Hg–Zn	300†	0.33	440	0.42	4.89
In–Mg	700	0.60	−7 300	—	—
In–Pb	400	0.48	963	0.50	6.29
In–Sb	627	0.45	3 300	0.50	6.51
In–Sn	427	0.45	−200	0.48	6.76
In–Tl	500	0.42	575	0.50	5.48
In–Zn	427	0.58	3 235	0.53	6.99
K–Na	111	0.40	737	0.50	5.66
Mg–Pb	700	0.40	−10 050	0.53	5.21
Mg–Sn	500	0.40	−14 650	—	—
Mg–Tl	650	0.40	−7 040	0.57	6.66
Mg–Zn	700	0.60	−6 490	—	—
Na–Rb	111	0.42	1 260	—	—
Na–Pb	427	0.40	−17 100	0.05 0.20 0.80	0.34 −2.85 2.26
Ni–Pd	1 600	0.50	1 200	0.50	5.41
Pb–Sb	632	0.55	−75	0.50	6.21
Pb–Sn	777	0.50	1 370	0.55	4.81
Pb–Tl	500	0.55	−1 090	0.50	5.22
Sb–Sn	632	0.50	−1 390	0.50	6.08
Sn–Tl	500	0.45	724	0.47	5.17
Sn–Zn	477	0.57	3 220	0.54	7.93

N_2 = mol fraction of second component.
* or † indicates that the standard state for the first or second component, respectively, is the hypothetical supercooled liquid.

Table 8.7a LIQUID BINARY METALLIC SYSTEMS AND SOME SOLID SOLUTIONS
Partial molar free energies ($-\overline{\Delta G}$) in kJ
For the solution of 1 g-atom of metal C in a theoretically infinite amount of alloy of concentration N_c (mol fraction of the dissolved metal), $-\overline{\Delta G}$ is given in kJ.

System	*Metal C*	*Temp.*°C	N_c: 0.1	0.2	0.3	0.5	0.8
Ag–Al (sol.)	Al	449	37.36	s+s	20.33	s+s	s+s
Ag–Al (liq.)	Al	1 000	51.81	36.57	23.40	8.73	2.26
Ag–Au (sol.)	Ag	527	25.87	19.46	15.03	8.54	2.20
Ag–Au (liq.)	Ag	1 077	32.99	24.16	18.51	10.63	3.01
Ag–Cd (sol.)	Cd*	400*	34.87α	26.41α	19.01α	10.47ζ	1+s

*Note standard state for metal *C*.

Table 8.7a LIQUID BINARY METALLIC SYSTEMS AND SOME SOLID SOLUTIONS—*continued*

System	*Metal C*	*Temp°C*	N_c: 0.1	0.2	0.3	0.5	0.8
Ag–Cd (liq.)	Cd	950	42.41	29.53	20.91	10.03	2.40
Ag–Cu (liq.)	Cu	1 150	15.94	10.20	7.41	4.58	2.06
Ag–Hg (sol.)	Hg*	227*	19.28α	12.32α	6.24α	l+s	l+s
Ag–Mg (sol.)	Mg	500	63.56α	51.33α	s+s	32.57β′	l
Ag–Pb (liq.)	Pb	1 000	20.99	13.56	9.51	5.50	1.96
Ag–Pd (sol.)	Ag	927	25.85	21.00	18.16	13.52	3.49
Ag–Sn (liq.)	Sn	977	25.34	21.02	17.68	11.50	3.50
Ag–Tl (liq.)	Tl	702	s	l+s	(5.31)	2.77	1.20
Ag–Zn (sol.)	Zn*	600*	30.96α	26.04α	19.69α	11.57β	s+l
Al–Mg (liq.)	Mg	800	31.26	21.21	14.97	7.42	2.01
Al–Zn (sol.)	Zn	380	3.34	1.99	1.64	1.41	s+s
Al–Zr (liq.)	Zn	727	13.52	8.88	6.78	4.42	1.45
Au–Bi (liq.)	Bi	700	l+s	l+s	10.45	5.11	1.94
Au–Cd (sol.)	Cd*	427*	51.92α	44.12α	$35.16\alpha_2$	18.84β	l
Au–Cd (liq.)	Cd	727	s	s	(38.0)	19.05	3.33
Au–Cu (sol.)	Cu	527	28.90	23.41	19.24	11.88	2.17
Au–Cu (liq.)	Cu	1 277	49.19	36.15	27.32	14.95	3.84
Au–Fe (sol.)	Fe	850	17.27	8.95	4.44	0.44	s+s
Au–Hg (sol.)	Hg*	227*	9.41α	3.20β	l+s	l+s	l+s
Au–Pb (liq.)	Pb	927	l+s	23.71	17.34	9.15	2.83
Au–Sn (liq.)	Sn	550	l+s	44.03	30.87	13.51	2 28
Au–Tl (liq.)	Tl	700	l+s	l+s	(13)	8.00	2.19
Au–Zn (liq.)	Zn	807	s	68.04	51.84	26.32	3.86
Bi–Cd (liq.)	Cd	500	15.28	11.10	8.61	5.07	1.34
Bi–Hg (liq.)	Hg	321	9.77	6.52	4.69	2.52	0.74
Bi–K (liq.)	K	575	87.44	78.57	70.33	48.10	l+s
Bi–Mg (liq.)	Mg	702	60.04	54.44	50.17	42.48	3.73
Bi–Pb (liq.)	Pb	427	17.24	12.52	9.48	5.27	1.43
Bi–Sn (liq.)	Sn	327	10.76	7.36	5.43	3.11	2.01
Bi–Tl (liq.)	Tl	477	25.15	21.10	17.73	10.90	2.50
Bi–Zn (liq.)	Zn	600	9.96	5.61	3.35	1.01	0.21
Cd–Cu (liq.)	Cu*	600*	16.01	12.34	10.22	6.60	l+s
Cd–Ga (liq.)	Ga	427	4.71	2.92	1.96	1.28	0.77
Cd–In (liq.)	In	527	11.37	8.15	6.35	3.84	1.34
Cd–Mg (sol.)	Mg	270	24.45	19.38	15.57	7.87	1.42
Cd–Na (liq.)	Na	400	21.30	11.42	6.21	2.02	0.76
Cd–Pb (liq.)	Pb	500	7.30	4.91	3.83	2.62	1.15
Cd–Sb (liq.)	Sb*	500*	24.62	18.97	14.19	6.29	l+s
Cd–Sn (liq.)	Sn	500	11.62	7.96	5.97	3.62	1.33
Cd–Zn (liq.)	Zn	527	8.88	5.62	4.18	2.53	1.04
Co–Fe (liq.)	Fe	1 590	30.29	21.09	16.05	10.21	3.65
Co–Fe (sol.)	Co, Fe	both solutes approx. ideal in γ phase					
Co–Pt (sol.)	Pt	1 000	64.59	48.82	37.08	19.75	4.35
Cr–Fe (solα)	Cr	1 327	23.75	16.60	12.82	8.10	2.70
Cr–Mo (sol.)	Cr	1 198	15.15	9.14	6.25	3.64	1.59
Cr–Ni (sol.)	Cr	1 277	35.76β	21.39β	12.24β	5.79β	α
Cr–V (sol.)	Cr	1 277	37.96	28.36	22.66	14.17	3.88
Cu–Fe (liq.)	Cu	1 600	8.86	4.81	3.78	2.85	1.66
Cu–Ni (sol.)	Ni	700	10.34	6.28	4.12	2.21	1.08
Cu–Pb (liq.)	Cu	1 200	12.18	6.74	4.53	2.88	1.96
Cu–Pt (sol.)	Cu	1 077	54.27	41.52	32.98	20.38	5.44
Cu–Sn (liq.)	Sn	1 127	57.37	30.57	18.93	8.87	2.84
Cu–Zn (sol.)	Zn*	500*	38.91α	29.67α	22.05α	(14.4β)	2.28ε
Cu–Zn (liq.)	Zn	1 060	42.58	31.28	23.66	12.94	—
Fe–Mn (liq.)	Mn	1 590	32.24	22.19	16.58	9.71	3.26

*Note standard state for metal *C*.

Table 8.7a LIQUID BINARY METALLIC SYSTEMS AND SOME SOLID SOLUTIONS—*continued*

System	*Metal C*	*Temp.°C*	N_c: 0.1	0.2	0.3	0.5	0.8
Fe–Ni (sol.)	Fe	927	—	—	13.02γ	7.45γ	2.30γ
Fe–Ni (liq.)	Ni	1 600	41.87	30.82	24.39	15.38	4.36
Fe–Ni (liq.)	Fe	1 600	48.15	33.54	23.75	11.74	3.60
Fe–Si (liq.)	Si	1 600	126.53	97.62	68.68	23.35	4.64
Fe–V (sol.)	V	1 327	59.24α	41.78α	30.21α	15.43α	3.91α
Ga–Mg (liq.)	Mg	650	43.89	35.68	28.86	17.50	3.04
Ga–Zn (liq.)	Zn	477	12.03	8.11	5.93	3.38	1.15
Hg–K (liq.)	K	327	69.98	44.39	25.56	6.33	1.09
Hg–Na (liq.)	Na	400	64.02	46.64	32.22	12.25	1.62
Hg–Pb (liq.)	Pb	327	68.61	56.51	47.76	33.45	1.22
Hg–Tl (liq.)	Tl*	25*	8.46	5.43	3.64	l+s	l+s
Hg–Zn (liq.)	Zn*	300*	8.12	5.55	4.08	2.26	l+s
In–Sb (liq.)	Sb	627	31.33	23.07	16.56	8.08	1.88
In–Zn (liq.)	Zn	427	6.41	3.53	2.05	1.21	0.51
K–Pb (liq.)	Pb	575	49.77	42.69	35.17	17.78	2.24
K–Tl (liq.)	Tl	525	27.17	24.20	21.65	14.58	3.22
Mg–Pb (liq.)	Mg	700	38.47	33.45	28.97	19.10	4.84
Mg–Sn (liq.)	Mg	800	55.98	47.77	40.53	25.86	6.26
Mg–Zn (liq.)	Mg	650	32.26	22.51	16.22	8.37	2.24
Mn–Ni (sol.)	Mn	777	61.76γ	43.10γ	33.35γ	17.22η	(2.1γ)
Na–Pb (liq.)	Na	427	45.92	38.70	30.82	19.05	3.14
Na–Sn (liq.)	Na	500	48.76	41.44	34.95	s	2.68
Na–Tl (liq.)	Na	400	41.06	32.05	24.07	10.47	1.47
Pb–Sb (liq.)	Pb	632	18.86	13.32	9.99	5.69	1.75
Pb–Sn (liq.)	Sn	777	9.27	7.37	6.57	4.79	1.80
Pb–Tl (liq.)	Tl	500	16.32	11.90	9.16	5.43	1.41
Sb–Sn (liq.)	Sn	632	22.73	16.40	12.34	6.89	1.97
Sb–Zn (liq.)	Zn	677	l+s	18.82	15.12	8.10	0.81
Sn–Tl (liq.)	Tl	450	9.93	6.71	5.06	3.15	1.20
Sn–Zn (liq.)	Zn	477	10.49	6.54	4.46	2.22	0.84

* Note standard state for metal *C*.

Table 8.7b LIQUID BINARY METALLIC SYSTEMS AND SOME SOLID SOLUTIONS
Partial molar heats of solution ($\overline{\Delta H}$) in kJ

System	*Metal C*	*Temp.°C*	N_c: 0.1	0.2	0.3	0.5	0.8
Ag–Al (liq.)	Al	1 000	−27.43	−18.71	−8.98	+5.53	+1.31
Ag–Au (sol.)	Ag	527	−14.28	−11.72	−9.29	−5.07	−0.88
Ag–Cd (sol.)	Cd*	400*	−23.42	−18.96	−15.42	—	—
Ag–Cu (liq.)	Cu	1 150	15.70	10.76	7.48	3.77	0.63
Ag–Mg (sol.)	Mg	500	−38.45	−31.18	(26.3)	—	—
Ag–Pb (liq.)	Ag	1 000	11.05	9.56	7.76	3.73	0.17
Ag–Zn (sol.)	Zn*	600*	−14.22	−11.08	− 9.41	−7.89β	l+s
Al–Mg (liq.)	Mg	800	−11.86	−9.14	−6.61	−2.68	−0.21
Al–Zn (sol.)	Zn	380	11.93	8.99	6.30	3.79	s+s
Al–Zn (liq.)	Zn	727	8.35	6.51	4.94	2.64	0.46
Au–Bi (liq.)	Bi	700	l+s	l+s	1.77	0.70	0.04
Au–Cd (sol.)	Cd*	427*	−55.26	−49.42	−39.31α_2	−20.32β	ε+l
Au–Cu (sol.)	Cu	527	−12.37	−12.00	−10.92	−7.39	−0.37
Au–Fe (sol.)	Fe	850	18.48	14.14	12.02	9.67	s+s
Au–Pb (liq.)	Pb	927	−3.05	−2.18	−1.14	−0.09	+0.60
Au–Sn (liq.)	Sn	550	l+s	−32.83	−22.70	−9.31	−0.48
Au–Zn (liq.)	Zn	807	s	−61.04	−48.12	−25.20	−1.93
Bi–Cd (liq.)	Cd	500	2.29	1.81	1.41	1.13	0.63
Bi–In (liq.)	In	627	−5.02	−4.80	−3.64	−2.35	−0.19
Bi–Na (liq.)	Na	500	−54.93	−66.36	−68.34	(−54)	l+s

* Note standard state for metal *C*.

Table 8.7b LIQUID BINARY METALLIC SYSTEMS AND SOME SOLID SOLUTIONS—*continued*

System	*Metal C*	*Temp* °C	N_c: 0.1	0.2	0.3	0.5	0.8
Bi–Pb (liq.)	Pb	427	−3.35	−2.90	−2.29	−1.07	−0.09
Bi–Sn (liq.)	Sn	327	0.34	0.27	0.20	0.10	0.02
Bi–Tl (liq.)	Tl	477	−10.96	−9.33	−7.89	−7.18	−1.12
Bi–Zn (liq.)	Zn	600	12.22	10.81	9.11	6.20	1.59
Cd–Ga (liq.)	Cd	427	9.19	6.60	4.89	2.67	0.84
Cd–Hg (liq.)	Cd	327	−7.85	−7.09	−5.66	−2.47	0.31
Cd–Mg (sol.)	Mg	270	−14.88	−14.39	−12.29	−5.92	−0.34
Cd–In (liq.)	Cd	527	14.15	3.54	2.89	1.70	0.39
Cd–Pb (liq.)	Cd	500	7.89	6.54	5.28	3.14	0.84
Cd–Sb (liq.)	Cd	500	1+s	1+s	(−4.5)	−3.24	+0.45
Cd–Sn (liq.)	Cd	500	5.45	4.40	3.52	2.16	0.52
Cd–Tl (liq.)	Cd	477	6.49	5.56	4.65	2.80	0.65
Cd–Zn (liq.)	Zn	527	6.82	5.37	4.04	2.12	0.40
Cr–V (sol.)	Cr	1 277	−7.48	−2.62	+4.43	−7.70	−1.49
Cu–Ni (sol.)	Ni	700	3.52	3.96	3.94	2.93	0.69
Cu–Pb (liq.)	Cu	1 200	21.70	16.80	13.06	6.99	1.96
Cu–Pt (sol.)	Cu	1 077	−28.65	−27.41	−25.30	−13.10	−3.33
Cu–Zn (sol.)	Zn*	500*	−28.69	−24.65	−17.36	(−15.7β)	−2.40ε
Fe–Mn (sol.)	Mn	1 177	−12.36	−10.95	−9.59	−6.61	−1.65
Fe–Ni (sol.)	Ni	927	−4.31	—	−8.83	−5.99	—
Fe–Ni (liq.)	Ni	1 600	−9.77	—	−9.72	−7.22	—
Fe–Si (liq.)	Si	1 600	−125.15	−109.73	−81.20	−27.80	−1.82
Fe–V (sol.)	Fe	1 327	−9.29	−5.98	−0.57	+14.17	+10.71
Ga–Zn (liq.)	Zn	477	4.52	3.73	3.08	2.01	0.51
Hg–Na (liq.)	Na	400	−72.24	−61.52	−40.18	−10.88	−0.35
Hg–Pb (liq.)	Hg	327	−0.73	+0.16	+0.65	+0.96	+0.45
Hg–Sn (liq.)	Sn*	177*	3.61	2.23	1.41	0.62	1+s
Hg–Tl (liq.)	Tl*	25*	−4.37	−2.78	−2.06	1+s	1+s
In–Pb (liq.)	In	400	2.98	2.40	1.88	1.00	0.17
In–Sn (liq.)	In	427	−0.59	−0.46	−0.38	−0.21	−0.04
In–Tl (liq.)	Tl	350	2.12	1.51	1.05	0.42	0.04
In–Zn (liq.)	Zn	427	9.50	7.98	6.50	3.78	0.91
Na–Pb (liq.)	Na	427	−39.05	−37.55	−34.32	−23.86	−3.43
Na–Tl (liq.)	Na	400	−33.33	−30.22	−24.70	−10.98	−0.67
Pb–Sb (liq.)	Pb	732	−0.14	−0.20	−0.19	−0.04	+0.03
Pb–Sn (liq.)	Sn	777	4.69	3.48	2.59	1.34	0.25
Pb–Tl (sol.)	Tl	250	−4.50	−4.20	−3.98	−2.93	−1.08
Pb–Tl (liq.)	Tl	500	−3.11	−2.67	−2.18	−1.15	−0.15
Sb–Sn (liq.)	Sn	632	−4.02	−3.56	−2.91	−1.50	−0.15
Sb–Zn (liq.)	Zn	577	1+s	−4.73	−5.39	−2.70	+0.96
Sn–Tl (liq.)	Tl	450	2.70	1.94	1.28	0.41	0.08
Sn–Zn (liq.)	Zn	477	8.22	7.47	6.43	4.13	1.35

*Note standard state for metal *C*.

8.5 Metallurgically important compounds

In Tables 8.8a to 8.8j values of the heats and free energies of formation from the constituent elements are given throughout in kJ mol^{-1} of compound and standard entropies in J K^{-1} mol^{-1} of compound. It is to be noted that the minus signs appear in the captions, and therefore positive numerical values denote exothermic formation.

The standard state of a reactant element is the most stable form at the temperature indicated unless otherwise stated in the headings; the ideal diatomic gases were used as the standard states for sulphur, bromine and iodine in computing the free energy values at room temperature. The standard state of the compounds is the ideal stoichiometric proportion, and the state of

aggregation where necessary is indicated by s = solid, m = liquid and g = gaseous. Many compounds are stable with slight deviations from stoichiometric proportion. Compounds which may exist over a range of composition are indicated by an asterisk (*). For such compounds thermochemical values must be used with caution; dissociation pressures calculated from the free energy values may show considerable deviations from measured dissociation pressures.

Free energy values are given at five temperatures; further values can be obtained by linear interpolation provided that no change in the state of aggregation occurs in the interval. Even then, a linear interpolation will generally give a value within the accuracy of the data. The limits of accuracy are given in the last column of the tables; they apply to the values of the heat and free energy of formation below, say, 1 500 K. The errors may be greater at 2 000 K.

Dissociation pressures of sulphides and phosphides have only been determined for parts of many systems, the data for the lowest oxidation steps often being absent. No total thermochemical values for the formation of the compounds from the elements can therefore be given in Tables 8.8f and 8.8j but dissociation pressures of the compounds rich in sulphur or phosphorus appear in Tables 8.9a and 8.9b, respectively.

The thermochemical values for the metal borides and carbides suggested below can only be used as a guide. They are not sufficiently reliable for accurate calculations—mainly for two reasons. (1) transition metals do not form stoichiometric compounds with boron and carbon but rather extensively homogeneity ranges of which the investigators have taken too little heed. Thus the data below are oversimplifications. (2) it is very doubtful whether the experimental zero-point entropies of borides and carbides are generally zero. More likely, 'frozen-in disorder' of the substances studied accounted for substantial zero-point entropies, so that the values in column 3 when obtained from low-temperature heat capacities are not truly 'standard entropies'.

Table 8.8a BORIDES
Heats and free energies of formation in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1227°C	*Accuracy* ±kJ
AlB_2	67.0	—	—	—	—	—	12
AlB_{12}	201.0	—	—	—	—	—	15
CeB_6	351.6	74.1	344.0	338.9	326.2	313.5	100
Co_2B	125.6	59.9	123.8	122.5	119.5	116.4	30
CoB	94.2	30.6	92.6	91.1	89.8	86.2	25
CrB	75.3	24.1	73.6	72.5	69.6	66.8	25
CrB_2	94.2	26.2	91.4	89.5	84.7	80.0	25
Fe_2B	71.2	56.7	70.1	69.3	67.4	65.5	20
FeB	71.2	27.7	69.6	68.5	65.8	63.1	20
HfB_2	336.1	42.7	332.2	329.5	323.0	316.5	10
MgB_2	92.1	36.0	89.6	88.0	83.0	60.0	25
MgB_4	105.1	51.9	103.8	103.0	100.4	77.5	25
MnB	75.3	32.4	73.7	72.6	70.0	67.3	30
MnB_2	94.2	34.5	91.4	89.6	85.0	80.4	30
NbB_2	251.2	37.7	248.0	245.9	240.6	235.2	25
Ni_4B_3	311.9	114.7	305.2	300.7	289.7	278.6	60
NiB	100.5	30.1	98.8	97.7	94.9	92.1	25
TaB_2	209.3	44.4	206.7	204.9	200.5	196.1	40
TiB_2	342.0	28.5	319.9	317.2	310.4	303.6	5
UB_2	164.5	55.1	162.1	160.6	156.6	152.7	25
UB_4	245.7	71.2	244.9	244.4	243.1	241.8	40
UB_{12}	433.2	139.8	438.8	442.6	452.0	461.4	40
ZrB_2	324.0	36.0	319.6	316.7	309.3	302.0	10

Table 8.8b CARBIDES
Heats and free energies of formation in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
Al_4C_3	215.8	88.7	203.6	—	174.1	153.3	122.2	8
B_4C	71.6	27.09	71.2	70.8	69.8	68.7	67.4	19
Be_2C	117.2	16.3	114.8	—	—	100.9	78.8	5
CaC_2	59.0	70.3	64.5(α)	69.5(α)	85.0(β)	103.0(β)	121.0(β)	13
Ce_2C_3	176.6	173.7	—	—	—	—	—	7
CeC_2	97.1	90.4	—	—	—	—	—	7
Co_2C	−16.7	74.5	−19.3	−12.1	−8.0	—	—	21
Cr_4C	98.4	135.6	100.0	72.0	104.2	118.3	—	9
Cr_7C_3	228.1	200.9	223.4	237.1	245.9	254.3	—	13
Cr_3C_2	109.7	85.4	108.6	109.8	115.3	122.4	—	13
Fe_3C	−25.1	104.7	−19.0	−14.2	−1.93	+4.90	—	4
CH_4	74.90(g)	186.3(g)	50.7(g)	32.7(g)	−19.3(g)	—	—	4
Mg_2C_3	−79.5	−62.8	—	—	—	—	—	33
MgC_2	−87.9	—	−84	—	—	—	—	21
Mn_7C_3	112.2	239.0	111.4	112.6	118.9	113.9	—	13
Nb_2C	186.3	64.0	—	—	—	—	—	13
NbC	138.1	35.1	—	—	—	—	—	—
SiC	67.0	16.54	—	58.2	55.3	53.2	41.9	9
Ta_2C	203.0	83.6	—	—	—	—	—	17
TaC	143.6	42.2	142.2	—	141.0	137.8	—	8
ThC	125.6	59	—	—	—	—	—	13
ThC_2	117.2	70.3	—	124.3	117.2	—	—	21
TiC	183.8	24.3	180.0	177.9	172.9	167.1	160.4	13
UC	90.9	59.5	92.1	93.4	96.7	95.5	92.5	13
U_2C_3	205.1	138.4	205.2	205.2	206.4	199.3	187.1	17
UC_2	96.3	67.8	98.4	100.0	101.7	99.6	93.8	13
VC	100.9	27.6	—	—	94.6	91.3	80.4	17
WC	37.7	41.8	37.3	36.4	35.6	34.8	33.5	13
W_2C	26.4	—	—	—	—	—	—	7
ZrC	202.0	33.1	198.3	196.2	190.7	184.4	—	21

Table 8.8c NITRIDES
Heats and free energies of formation in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
AlN	318.6	20.2	287.1	266.1	—	—	—	5
BN	254.1	14.8	—	—	—	48.1	27.6	5
Ba_3N_2	341.1	(152.4)	292.2	244.1	123.9	—	—	38
Be_3N_2	589.9	34.3	534.1	—	—	—	—	5
Ca_3N_2	439.6	108.0	377	335	230	—	—	23
Cd_3N_2	−161.6	—	—	—	—	—	—	13
CeN	326.6	—	295.2	274.2	222	—	—	38
Co_3N	−8.4	98.8	—	—	—	—	—	21
CrN	123.1	—	96.7	78.7	40.6	—	—	5
Cr_2N	114.7	—	93.8	79.5	51.1	28.0	—	5
Cu_3N	−74.5	—	—	—	—	—	—	13
Fe_4N	10.9	(156.2)	−4.2	−12.77	−41.0	—	—	17
GaN	109.7	29.7	—	—	—	—	—	10
Ge_3N_4	65.3	(167)	—	—	—	—	—	9

Table 8.8c NITRIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1227°C	$-\Delta G_{2000}$ 1727°C	*Accuracy* ±kJ
HfN	369.3	50.6	—	—	—	—	—	2.5
NH_3	46.1	192.47	16.7	−4.6	−61.5	—	—	2.1
InN	138.1	43.5	—	—	—	—	—	13
LaN	299.4	44.4	270.5	249.5	197.2	—	—	38
Li_3N	196.8	—	154.1	125.6	—	—	—	2.1
Mg_3N_2	461.8	93.7	399.4	359.6	258.3	—	—	13
Mn_4N	126.9	—	—	—	—	—	—	4
Mn_5N_2	201.8	—	156.2	125.6	49.4	—	—	4
Mo_2N	69.5	(87.9)	70.8	37.3	−8.8	—	—	17
NbN	234	—	—	—	—	—	—	11
Nb_2N	248.6	67.0	—	—	—	—	—	4
Ni_3N	−0.8	—	−27.2	—	—	—	—	4
Si_3N_4	745.1	113.0	622.2	571.9	410.3	251.2	64.5	17
Sr_3N_2	391.0	123.5	323.6	278.4	—	—	—	23
Ta_2N	270.9	—	—	—	—	—	—	13
TaN	252.4	42.7	214.8	202.2	166.6	134.0	103.8	13
Th_3N_4	1 298.0	—	1 185	1 114	925	737	548	84
TiN	336.6	30.1	308.1	289.7	243.3	195.9	148.2	8
UN	294.7	62.7	260.0	242.0	196.8	152.0	106.7	42
U_2N_2	708.5	128.9	—	—	—	—	—	17
VN	217.3	37.3	—	—	—	—	—	17
V_2N	264.5	53.4	—	—	—	—	—	17
Zn_3N_2	22.2	140.2	—	—	—	—	—	8
ZrN	365.5	38.9	336.2	317.8	270.9	223.2	—	7

Table 8.8d SILICIDES
Heats and free energies of formation in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1227°C	*Accuracy* ±kJ
Ca_2Si	209.3	—	—	—	—	—	13
CaSi	150.7	—	—	—	—	—	9
$CaSi_2$	150.7	—	—	—	—	—	13
Co_2Si	117.2	—	—	—	—	—	10
CoSi	95.0	42.7	93.2	91.9	88.9	85.8	9
$CoSi_2$	98.8	64.0	97.7	97.0	95.1	95.5	12
Cr_3Si	92.1	86.3	90.8	90.0	87.9	85.8	18
Cr_5Si_3	211.4	16.91	209.4	280.0	204.6	201.2	35
CrSi	53.2	43.9	53.6	53.8	54.4	55.0	10
$CrSi_2$	80.0	58.6	78.5	77.5	75.1	72.7	13
FeSi	76.9	41.8	75.6	74.8	72.7	70.9	5
Mg_2Si	79.1	63.8	73.1	69.1	55.0	—	5
Mn_2Si	79.5	103.8	76.4	74.3	69.0	63.8	15
Mn_5Si_3	200.9	238.6	207.8	212.5	224.0	235.6	40
MnSi	60.7	46.5	59.5	58.6	56.6	54.5	13
Mn_4Si_7	308.5	228.1	299.3	293.1	277.7	262.3	65
Mo_3Si	116.4	106.5	117.0	117.4	118.3	119.3	7.5
Mo_5Si_3	310.2	208.0	312.8	314.5	318.8	323.1	25
$MoSi_2$	131.9	65.1	131.6	131.4	130.8	130.3	10
$NbSi_2$	138.1	69.9	136.8	136.0	133.9	131.7	45
Ni_2Si	142.7	—	—	—	—	—	11
Ni_3Si_2	232.3	—	—	—	—	—	20
NiSi	89.6	44.4	88.4	87.5	85.4	83.3	7.5
$NiSi_2$	94.2	65.3	93.6	93.1	92.1	91.0	13
Re_5Si_3	157.4	256.0	161.3	164.0	170.5	177.1	70

Table 8.8d SILICIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	*Accuracy* ±kJ
ReSi	52.7	55.4	52.5	52.4	52.0	51.7	21
$ReSi_2$	90.4	74.1	90.2	90.0	89.6	89.2	30
Ta_2Si	125.6	105.5	126.7	127.4	129.2	131.0	20
Ta_5Si_3	334.9	280.9	340.2	343.7	352.4	361.2	35
$TaSi_2$	119.3	75.3	118.2	117.5	115.6	113.8	13
Th_3Si_2	279.6	166.4	270.2	263.9	248.1	232.4	50
ThSi	126.0	62.8	123.2	121.3	116.6	111.9	17
Th_3Si_5	477.6	231.9	470.9	466.4	455.2	444.1	85
$ThSi_2$	170.8	89.2	170.3	169.9	169.0	168.1	30
Ti_5Si_3	579.8	—	—	—	—	—	65
TiSi	129.8	49.0	49.0	48.95	48.9	48.8	15
$TiSi_2$	134.4	61.1	132.0	131.0	127.6	124.2	21
U_3Si	92.1	167.4	91.5	91.1	90.1	89.1	13
U_3Si_2	170.8	197.6	173.6	175.5	180.2	184.9	11
USi	84.6	66.6	83.9	83.4	82.2	81.0	5
U_3Si_5	354.6	231.5	353.7	353.1	351.5	350.0	17
USi_2	129.8	82.0	127.1	126.9	124.0	121.1	3
USi_3	130.6	106.3	130.5	130.45	130.3	130.1	3

Table 8.8e OXIDES
Heats and free energies of formation in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
Ag_2O	30.6	121.8	10.68	—	—	—	—	2.1
Al_2O_3	1 678.2	51.1	1 584.0	1 520.8	1 362.4	1 146.9	—	17
As_2O_3	653.77	122.80	577.4	526.3	—	—	—	3.3
As_2O_5	914.8	105.5	771.6	675.7	—	—	—	6.3
B_2O_3	1 272.5	54.0	1 192.9	1 139.8	—	—	—	8
BaO	553.8	70.3	524.5	504.4	455.0	—	—	22
BaO_2	634.2	93.1	—	—	—	—	—	13
BeO	608.4	14.1	580.0	560.7	513.4	466.9	412.9	13
Bi_2O_3	570.7	151.6	496.6	—	—	—	—	17
CO	110.5	198.0	138.2	155.7	199.50	243.3	287.2	4
CO_2	393.77	213.9	394.4	394.8	395.2	395.7	396.1	4
CaO	634.3	39.8	603.7	584.1	534.7	481.9	405.7	4
CaO_2	659.4	—	—	—	—	—	—	4
CdO	259.4	54.8	229.7	212.1	204.1	106.6	—	4
Ce_2O_3	1 821.7	150.7	1 733.7	1 676.9	—	—	—	8
CeO_2	1 089.4	62.4	1 025.8	983.9	882.2	—	—	13
CoO	239.1	52.96	212.7	198.9	163.3	127.7	—	4
Co_3O_4	905.6	102.6	777.1	705.9	525.0	—	—	13
Cr_2O_3	1 130.4	81.2	1 051.3	991.0	861.6	731.0	601.2	17
CrO_2	582.8	51.0	—	—	—	—	—	8
CrO_3	579.9	71.9	—	—	—	—	—	10.5
Cs_2O	317.8	127.6	—	—	—	—	—	13
Cu_2O	167.5	93.8	144.9	129.8	95.5	59.5	—	4
CuO	155.3	42.7	127.3	108.9	66.6	—	—	4
Dy_2O_3	1 866.5	149.9	1 773.9	1 712.4	—	—	—	13
Er_2O_3	1 899.1	153.2	1 808.7	1 748.4	—	—	—	8
$Fe_{0.95}O$	264.6	58.82	241.2	228.6	197.2	165.8	—	13
Fe_3O_4	1 117.5	151.6	1 015.3	950.0	780.8	—	—	25
Fe_2O_3	821.9	87.5	—	695.0	556.8	—	—	21
Ga_2O	347.5	—	—	--	--	—	—	13

Table 8.8e OXIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
Ga_2O_3	1 083.5	84.78	992.3	—	—	—	—	8
Gd_2O_3	1 817.1	150.7	1 730.4	1 651.7	—	—	—	13
GeO	30.7(g)	224.0(g)	54.2(g)	69.2(g)	105.7(g)	—	—	17
GeO_2	580.2	39.7	525.3	488.7	397.1	—	—	8
H_2O	286.0(m)	70.13(m)	237.0(m)	—	—	—	—	0.8
H_2O	242.0(g)	188.8(g)	228.6(g)	219.0(g)	192.6(g)	164.1(g)	134.4(g)	1.3
H_2O_2	187.1(m)	109.5(m)	118.1(m)	—	—	—	—	2.1
H_2O_2	135.2(g)	226.9(g)	—	—	—	—	—	1.3
HfO_2	1 113.7	59.5	1 053.4	1 014.0	919.4	828.1	739.0	4
HgO (red)	90.9	70.3	58.32	36.59	—	—	—	4
Ho_2O_3	1 882.4	158.3	1 792.4	1 732.1	—	—	—	13
In_2O_3	927.4	—	834.0	771.6	—	—	—	13
IrO_2	241.5	56.5	186.1	149.2	57.0	—	—	17
IrO_3	−13.4(g)	290.5(g)	—	—	—	85.0	—	76
K_2O	363.3	—	320.7	295.2	229.4	163.3	—	3
KO_2	284.6	122.6	—	—	—	—	—	2.1
La_2O_3	1 794.1	128.1	1 706.2	1 648.4	1 509.0	—	—	8
Li_2O	596.6	37.93	560.2	534.2	467.7	—	—	4
Li_2O_2	635.6	—	—	—	—	—	—	8
MgO	601.6	26.97	571.1	550.1	498.6	440.5	329.9	6.3
MnO	385.2	59.9	363.0	348.8	312.3	275.9	234.5	13
Mn_3O_4	1 387.5	148.6	1 280.3	1 209.6	1 035.8	—	—	13
Mn_2O_3	960.5	110.5	882.2	821.9	703.8	—	—	13
MnO_2	520.4	53.2	462.2	424.5	334.9	—	—	13
Mn_2O_7	728.9	—	—	—	—	—	—	10.5
MoO_2	588.7	50.0	533.4	496.5	404.3	—	—	4
MoO_3	746.1	77.9	668.6	617.1	486.9	—	—	4
Na_2O	415.2	75.1	376.1	350.1	285.0	—	—	8
Na_2O_2	515.0	94.6	—	—	—	—	—	6.3
NaO_2	261.7	116.0	—	—	—	—	—	4
NbO	419.8	46.0	391.2	373.1	326.5	—	—	17
NbO_2	799.3	54.55	743.2	705.5	612.1	518.3	425.0	8
Nb_2O_5	1 900.8	137.3	1 766.0	1 676.4	—	—	—	13
Nd_2O_3	1 809.1	158.6	—	—	—	—	—	17
NiO	240.7	38.1	213.1	194.7	150.7	108.4	57.4	13
NpO_2	1 030.0	80.4	—	—	—	—	—	42
OsO_4	393.9	136.9	—	—	—	—	—	13
P_2O_5	1 493.0	229.0	1 381.6	—	—	—	—	25
PbO	219.4	66.3	188.8	168.3	117.2	—	—	13
Pb_3O_4	719.0	211.4	600.9	519.7	325.4	—	—	25
PbO_2	274.6	71.9	215.3	175.8	76.9	—	—	8
PdO	112.6	39.3	82.2	62.0	11.3	—	—	17
Pr_2O_3	1 828.8	158.6	—	—	—	—	—	6
$PrO_{1.72}$	937.8	—	—	—	—	—	—	6.3
PrO_2	974.9	80.0	—	—	—	—	—	17
PtO_2	−168.7(g)	256.0(g)	—	—	—	157.8	—	8
PuO_2	1 058.4	82.5	1 003.6	968.8	882.2	795	—	21
Rb_2O	330.3	—	—	—	—	—	—	13
Rb_2O_3	527.5	—	—	—	—	—	—	42
RbO_2	284.7	—	—	—	—	—	—	25
ReO_2	432.9	62.8	379.0	343.0	253.2	—	—	13
ReO_3	611.3	80.8	—	—	—	—	—	21
Re_2O_7	1 249.1	207.5	1 073.7	959.0	—	—	—	8
Rh_2O_3	383.0	92.1	—	—	—	—	—	17

Table 8.8e OXIDES—*continued*

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	$-\Delta G_{2000}$ 1 727 °C	*Accuracy* ±kJ
RhO_2	195.9(g)	263.8(g)	—	—	—	157.8	—	4
RuO_2	304.4	60.7	252.3	217.6	130.9	44.2	—	8
RuO_3	78.3(g)	276.2(g)	—	—	—	—	—	—
RuO_4	180.9(g)	290.1(g)	—	—	—	—	—	—
SO	−5.0(g)	222.3(g)	—	73.2(g)	70.3(g)	79.1(g)	82.0(g)	8
SO_2	297.05(g)	248.07(g)	340.8(g)	326.6(g)	290.1(g)	254.1(g)	217.7(g)	2.1
SO_3	395.2(g)	256.2(g)	—	376.4(g)	295.6(g)	214.4(g)	—	6.3
Sb_2O_3	699.2	123.1	—	—	—	—	—	13
SbO_2	454.0	63.6	—	—	—	—	—	25
Sb_2O_5	1 008.0	125.2	—	—	—	—	—	63
Sc_2O_3	1 906.7	77.0	1 818.7	1 756.8	—	—	—	—
SeO_2	236.1	66.7	—	—	—	—	—	4
SiO	98.4(g)	211.64(g)	126.9(g)	144.5(g)	185.1(g)	223.7(g)	—	13
SiO_2	910.9(q)	41.5(q)	—	—	726.9	640.0	538.5	13
Sm_2O_3	1 833.0	151.1	1 744.2	1 685.2	—	—	—	13
SnO	286.4	56.5	—	—	—	—	—	4
SnO_2	580.7	52.3	519.4	478.3	—	—	—	4
SrO	592.3	55.5	562.4	542.3	492.3	—	—	13
SrO_2	633.7	59.0	—	—	—	—	—	17
Ta_2O_5	2 047.3	143.2	1 910.9	1 822.1	1 612.8	1 413.0	1 220.0	21
Tb_2O_3	1 828.8	—	—	—	—	—	—	8
$TbO_{1.71}$	934.9	—	—	—	—	—	—	4
$TbO_{1.8}$	947.9	—	—	—	—	—	—	4
TcO_2	433.3	58.6	—	—	—	—	—	13
Tc_2O_7	1 113.7	184.2	996.0	917.7	722.2	—	—	17
TeO_2	322.4	74.1	268.3	232.2	138.6	—	—	8
ThO_2	1 227.6	65.3	1 173.6	1 135.0	1 048.8	960.9	—	21
TiO	542.9	34.8	509.5	491.9	447.1	402.7	352.9	17
Ti_2O_3	1521.6	77.3	1 427.1	375.8	245.7	1 116.5	986.4	17
Ti_3O_5	2 457.2	129.4	2 309.4	2 224.4	2 010.1	1 797.0	1 581.8	13
TiO_2	944.1	50.2	862.1	827.3	739.5	652.7	564.8	16
Tl_2O	167.4	134.3	—	—	—	—	—	4
Tl_2O_3	390.6	137.3	—	—	—	—	—	25
Tm_2O_3	1 889.9	—	—	—	—	—	—	8
UO_2	1 085.2	77.9	1 032.0	996.9	913.6	827.7	740.6	13
U_4O_9	4 513	336.2	—	—	—	—	—	42
U_3O_8	3 575.9	282.6	—	—	—	—	—	21
UO_3	1 230.7	98.8	—	—	—	—	—	21
VO	432.0	38.9	413.5	398.5	360.8	322.9	—	25
V_2O_3	1 219.4	98.4	1 147.0	1 099.7	982.0	864.4	—	33
VO_2	713.7	51.5	678.4	643.8	567.2	—	—	21
V_2O_5	1 551.3	131.0	1 454.1	1 373.7	1 172.8	—	—	50
WO_3	838.6	75.9						
WO_2	589.9	50.6	—	480.6	405.7	334.5	—	13
Y_2O_3	1 906.7	99.2	1 817.9	1 759.3	1 618.6	1 482.1	1 348.1	21
Yb_2O_3	1 815.8	133.1	—	—	—	—	—	8
ZnO	350.8	43.5	320.7	301.0	256.6	174.6	82.0	8
ZrO_2	1 101.3	50.7	1 042.2	1 003.7	909.9	818.2	729.5	17

Table 8.8f SULPHIDES
Heats and free energies of formation in kJ and standard entropies
In calculating the heats of formation, rhombic sulphur is taken as the standard state. For the free energies of formation the perfect diatomic gas S_2 is taken as the standard state at all temperatures.

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	ΔG_{500} 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	$-\Delta G_{2000}$ 1 727 °C	*Accuracy* ±kJ
Ag_2S	31.8(α)	144.4(α)	180.4(α)	70.8(β)	53.2(β)	32.2(m)	—	2.1
Al_2S_3	723.9	123.5	—	—	—	—	—	17
As_2S_3	167.4	169.6	—	—	—	—	—	23
B_2S_3	252.4	92.1	—	—	—	—	—	9
BaS	443.8	78.3	481.9	463.9	419.1	—	—	21
BeS	234.0	35.2	272	247	201	—	—	21
Bi_2S_3	201.8	200.5	—	—	—	—	—	—
CS_2	−87.9(m)	151.6(m)	15.1(g)	16.3(g)	19.7(g)	23.4(g)	—	4
COS	138.5	231.5	207.2	208.9	212.4	218.5	223.1	13
CaS	476.4	56.5	—	491.9	444.2	393.1	319.9	8
CdS	149.4	69.1	185.5	—	—	—	—	4
CeS	456.7	78.3	496.5	479.8	437.9	396.0	354.2	21
Ce_3S_4	1 653.5	255.3	—	—	—	—	—	17
Ce_2S_3	1 188.8	180.4	—	—	—	—	—	13
$CoS_{0.89}$	94.6	52.3	125.2	110.5	73.3	—	—	8
Co_3S_4	359.2	184.6	—	427.9	—	—	—	13
CoS_2	153.2	69.1	—	—	—	—	—	17
CrS	155.7	64.0	—	—	—	—	—	13
Cs_2S	339.5	—	—	—	—	—	—	33
Cu_2S	79.6	120.9	128.5	118.1	100.9	—	—	8
CuS	52.3	66.6	—	—	—	—	—	4
FeS	100.5	60.3	140.2(α)	126.4(β)	97.3(β)	—	—	4
FeS_2	171.6	53.2	—	299.8	90.9	—	—	8
GaS	209.3	57.7	—	—	—	—	—	13
Ga_2S_3	514.0	139.8	—	—	—	—	—	13
GeS	76.2	66.2	46.5	36.7	—	—	—	33
H_2S	20.1(g)	205.6(g)	73.7(g)	65.10(g)	41.24(g)	16.3(g)	−8.0(g)	2.1
HgS	53.4	82.5	—	—	—	—	—	6.3
InS	133.9	69.1	—	—	—	—	—	13
In_3S_6	774.4	174.6	—	—	—	—	—	84
In_2S_3	355.8	163.7	—	—	—	—	—	17
Ir_2S_3	244.5	97.1	—	—	124.8	10.5	—	33
IrS_2	144.8	61.6	—	—	—	—	—	25
K_2S	428.7	—	—	—	—	—	—	14.7
La_2S_3	1 222.3	165.1	1 235.5	—	—	—	—	42
Li_2S	446.6	60.7	—	—	—	—	—	8
MgS	351.6	50.4	—	—	296.8	—	—	8
MnS	213.5	80.4	254.3	241.7	211.0	128.5	143.2(m)	6.3
MnS_2	223.9	99.9	—	—	—	—	—	10.5
Mo_2S_3	410.2	113.0	—	—	309.4	195.1	—	29
MoS_2	275.4	62.6	—	—	203.1	125.2	—	21
Na_2S	374.6	79.5	—	388.1	322.4	206.8	—	17
NaS	201.3	44.8	—	—	—	—	—	14.7
NaS_2	206.0	83.7	—	—	—	—	—	14.7
Ni_3S_2	216.0	134.0	—	252.0	—	—	—	13
NiS	94.2	53.0	—	—	—	—	—	6.3
OsS_2	100.5	—	181.7	144.9	66.2	−8.8	—	17
PbS	98.4	91.3	134.6	120.6	81.7	—	—	4
PtS	82.5	55.06	116.4	96.3	47.7	0.8	—	13
PtS_2	110.1	74.73	179.6	141.1	49.4	—	—	13
Rb_2S	348.3	133.1	—	—	—	—	—	25
ReS_2	139.0	60.7	211.4	177.1	97.1	21.4	—	25
RuS_2	206.0	—	242.8	207.7	125.2	46.9	—	21

Table 8.8f SULPHIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
S	−277.1(g)	167.9(g)	—	−146.5(g)	−115.1(g)	−83.7(g)	−53.2(g)	0.5
S_2	−129.8(g)	228.2(g)	0(g)	0(g)	0(g)	0(g)	0(g)	4
S_6	−103.0(g)	354.0(g)	179.6	121.8	−23.4	—	—	13
S_8	− 99.6(g)	423.3(g)	258.7	174.2	−37.7	—	—	33
Sb_2S_3	205.1	182.1	285	230	—	—	—	29
SiS_2	213.5	80.4	278.4	—	—	—	—	25
SnS	108.4	77.0	143.6	—	—	—	—	6.3
SnS_2	153.6	87.5	—	—	—	—	—	17
SrS	452.6	69.1	488.6	468.5	419	—	—	42
Th_2S_3	1 082.7	—	—	—	—	—	—	10.5
TiS	272.1	56.5	—	—	—	—	—	33
Tl_2S	95.0	159.0	—	—	—	—	—	4
WS_2	202.6	83.7	278.4	243.7	162.4	85.4	—	17
ZnS	205.3	57.8	235.4	219.1	174.3	90.4	−4.9	17

Table 8.8g HALIDES

Heats and free energies of formation in kJ and standard entropies

For the free energies of formation the standard states for the halogens at all temperatures are the perfect diatomic gases at a pressure of one atmosphere.

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
AgF	206.0	83.7	185.5	173.8	161.2(m)	146.5(m)	—	8
AgF_2	359.6	—	304.8	276.3	213.5(m)	—	—	13
AgCl	126.9	96.3	109.3	98.8	80.4(m)	69.9(m)	—	0.8
AgBr	99.2	107.2	97.1	86.7	69.5(m)	65.7(m)	—	0.8
AgI	62.4	115.6	77.0	66.6	50.2	46.1	—	0.8
AlF	265.4(g)	215.2(g)	—	—	—	—	—	4
AlF_3	1 511.1	66.6	1 418.5	1 377.9	—	—	—	0.8
AlCl	51.5(g)	227.8(g)	75.3(g)	94.6(g)	133.5(g)	164.9(g)	196.1(g)	2
$AlCl_3$	705.9	110.1	572.3(g)	566.5(g)	334.7(g)	500.7(g)	—	4
Al_2Cl_6	1 275.3(g)	475.8	—	1 238.0(g)	1 194.9(g)	—	—	2
$AlBr_3$	511.3	180.3	515.0	—	—	—	—	2
AlI_3	310.2	189.6	—	—	—	—	—	6
AsF_3	958.0(m)	180.5(m)	—	—	—	—	—	4
AsF_3	921.7(g)	289.3(g)	—	—	—	—	—	4
$AsCl_3$	335.8(m)	233.6(m)	294.8(m)	278.0(g)	254.1(g)	217.7(g)	—	25
$AsBr_3$	132.1(g)	363.9(g)	—	—	—	—	—	6
AsI_3	64.9	213.1	94.6	61.5	—	—	—	10.5
AuF_3	365.4	114.3	—	—	—	—	—	36
AuCl	34.8	92.9	17.6	5.4	—	—	—	4
$AuCl_3$	115.1	148.2	57.4	18.8	—	—	—	8
AuBr	18.4	119.0	16.3	4.6	—	—	—	4
$AuBr_3$	54.4	—	44.0	4.2	—	—	—	21
AuI	−0.8	—	12.6	0.0	—	—	—	4
BF_3	1 136.1(g)	254.6(g)	—	—	—	—	—	2.1
BCl_3	427.0(m)	206.0(m)	—	—	—	—	—	13
BCl_3	403.1(g)	290.1(g)	—	—	—	—	—	13
BBr_3	238.6(m)	228.9(m)	—	—	—	—	—	2
BBr_3	204.2(g)	324.5(g)	—	—	—	—	—	2
BaF_2	1 207.6	96.3	1 146.3	1 112.4	1 035.8	952.5	—	13
$BaCl_2$	860.8	123.7	—	—	—	—	—	3

Table 8.8g HALIDES—*continued*

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	$-\Delta G_{2000}$ 1 727 °C	*Accuracy* ±kJ
$BaBr_2$	755.3	148.6	736.0	702.5	622.2	553.5	—	13
BaI_2	602.9	165.2	617.6	584.5	507.9(m)	447.2	—	21
BeF	175.0(g)	205.78(g)	236.6(g)	255.0(g)	299.8(g)	341.6(g)	378.5(g)	17
BeF_2	1 027.4	53.4	963.4	—	—	—	—	13
BeCl	−8.3(g)	217.7(g)	16.3(g)	35.6(g)	81.6(g)	125.2(g)	163.3(g)	—
$BeCl_2$	494.0	75.8	452.2	427.1	385.2(m)	—	—	8
$BeBr_2$	353.7	106.3	322	297	—	—	—	25
BeI_2	192.5	120.6	186.7	159.9	—	—	—	25
BiF_3	910.8	122.6	821	775	—	—	—	25
BiCl	−25.1(g)	255.1(g)	—	—	52.3(g)	—	—	17
$BiCl_3$	379.3	171.6	328.5	294.7	250.7	174.5	—	8
BiI_3	150.7	224.8	131.5	88	—	—	—	13
CF_4	933.5(g)	262.5(g)	888(g)	858(g)	782(g)	707(g)	—	21
CCl_4	135.3(m)	214.8(m)	68.2	—	—	—	—	2.1
CCl_4	103(g)	309.4(g)	—	36.0	—	—	—	4
CBr_4	−50.2(g)	358.4(g)	—	—	—	—	—	17
CaF_2	1 220.2	68.87	1 167.1	1,132.1	1 050.7	970.3	—	9
$CaCl_2$	796.2	104.6	752.4	724	653	599(m)	—	5
$CaBr_2$	680.4	134.0	663.6	633.0	562.3	502	—	10.5
CaI_2	535.1	142	551.4	519.6	498.4	385.6(m)		21
CdF_2	697.1	83.6	648.1	613.4	538.0	—	—	5
$CdCl_2$	391.0	115.3	—	—	—	—	—	2.1
$CdBr_2$	314.8	139.0	301.4	272.1	202.2	—	—	8
CdI_2	204.2	158.4	—	—	—	—	—	4
$CeCl_3$	1 058.4	147.8	981.8	932.0	818.5	—	—	8
CeI_3	650.4	214.7	679.1	631.4	520.4	424.1(m)	—	21
CoF_2	692.9	82.1	646.4	618.4	547.6	—	—	13
CoF_3	811.2	95.4	744.3	706.3	602.3	—	—	33
$CoCl_2$	310.2	109.3	425.5	239.5	174.2	150.3	—	5
$CoBr_2$	221.0	134.0	203.9	177.1	122.7(m)	(87.1)(m)	—	13
CoI_2	87.9	153.2	118.9	85.0	30.6(m)	−5.0(m)	—	21
CrF_2	779.9	89.7	—	—	—	—	—	13
CrF_3	1 113.9	93.95	1 043	996	879	762(m)	—	21
CrF_4	1 199.5	—	1 118	1 065.5	—	—	—	25
$CrCl_2$	395.6	115.3	351.3	327.0	272.1	233.6(m)	252.9(g)	13
$CrCl_3$	556.7	123.01	491.9	445.0	327.4	—	—	21
CrI_2	158.3	—	179.6	151.1	88.3	46.5(m)	—	21
CrI_3	205.1	199.6	—	—	—	—	—	21
CsF	555.1	88.3	527.5	507.0	458.8	416.9	—	8
CsCl	433.3	100.1	404.4	384.3	336.6	298.9	—	5
CsBr	394.8	113.5	382.3	361.7	318.2	284.7	—	13
CsI	337.0	—	340.4	318.6	273.0	250.0	—	10.5
CuF_2	549.2	—	502.2	475.9	411.3	—	—	17
CuCl	137.3	87.1	117.2	105.9	93.8	81.6	—	8
$CuCl_2$	217.6	108.4	163.3	132.7	—	—	—	13
CuBr	104.3	96.3	101.3	89.6	70.8	55.7	—	4
$CuBr_2$	141.9	133.9	126.9	98.4	—	—	—	18.8
CuI	67.8	96.7	79.5	65.7	39.4	23.9	—	4
CuI_2	7.1	—	—	—	—	—	—	10.5
$ErCl_3$	959.2	146.9	—	—	—	—	—	4
FeF_2	711.6	87.1	667.6	640.8	574.3		—	25
FeF_3	1 042.3	98.4	975	929	824	728(m)	—	54
$FeCl_2$	341.2	120.2	304.4	279.7	222.7(m)	209.88	—	1.7
$FeCl_3$	400.7	142.3	—	—	—	—	—	4
$FeBr_2$	247.4	140.0	239.1	213.1	160.8	127.3(m)	—	4

Table 8.8g HALIDES—*continued*

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	$-\Delta G_{2000}$ 1 727 °C	*Accuracy* ±kJ
$FeBr_3$	265.9	173.7	250.4	213.5	—	—	—	17
FeI_2	116.4	170.0	149.5	122.7	68.2(m)	32.7(m)	—	17
$GaCl_3$	523.4	135.2	466.8	431(m)	—	—	—	6.3
$GaBr_3$	386.9	180.0	375.1	339(m)	—	—	—	4
GaI_3	239.4	203.8	248.3	209(m)	—	—	—	13
$GdCl_3$	1 005.3	146.1	—	—	—	—	—	4
GeF_4	1 192.5(g)	302.9(g)	—	—	—	—	—	2
$GeCl_4$	504.8(g)	347.5(g)	463	—	—	—	—	—
$GeBr_4$	330.8	396.9	309.0	266.3(g)	—	—	—	10.5
GeI_4	37.7(g)	429.1(g)	—	—	—	—	—	13
HF	272.7(g)	173.8(g)	273.4(g)	274.7(g)	277.2(g)	278.8(g)	279.7(g)	8
HCl	92.4(g)	186.94(g)	95.0(g)	96.7(g)	100.5(g)	103.4(g)	107.2(g)	1.3
HBr	36.4(g)	198.9(g)	57.65(g)	59.58(g)	63.35(g)	66.65(g)	69.75(g)	1.3
HI	−26.4(g)	206.8(g)	7.70(g)	9.67(g)	13.57(g)	17.2(g)	21.52(g)	1.3
HfF_4	1 931.8	136.0	—	—	—	—	—	8
$HfCl_4$	991.9	190.9	898.9	—	—	—	—	17
HgF	246.2	—	219.0	—	—	—	—	21
HgF_2	397.7	—	—	—	—	—	—	42
HgCl	131.9	98.4	104.7	85.4	—	—	—	1.3
$HgCl_2$	230.3	144.4	183.4	153.2	—	—	—	4
HgBr	103.4	111.4	92.1	72.9	—	—	—	1.3
$HgBr_2$	169.6	162.9	152.0	121.0	—	—	—	1.3
HgI	60.3	121.4	66.2	48.6	—	—	—	0.8
HgI_2	105.5	170.8	119.3	87.5	—	—	—	1.7
InCl	186.3	95.0	180	163(m)	—	—	—	10.5
$InCl_2$	362.9	122.2	315.1	—	—	—	—	18
$InCl_3$	537.5	141.0	465	425.0	327(m)	—	—	13
InBr	173.8	113.9	—	—	—	—	—	8
$InBr_3$	411.1	178.7	352	306	—	—	—	13
InI	116.4	131.5	—	—	—	—	—	8
InI_3	249.1	—	285	247(m)	—	—	—	13
IrCl	67.0	—	50	42	8	—	—	13
$IrCl_2$	138.2	—	99.2	71	8	—	—	13
$IrCl_3$	254.5	114.9	—	—	—	—	—	13
KCl	436.9	82.5	409.1	389.0	338.7	267.1(m)	223.6(g)	2
KBr	394.0	96.7	379.7	360.9	313.6	280.1(m)	—	3
KF	568.9	66.6	532.6	510.4	455.9	416.2(m)	—	3
KI	327.8	104.3	332.0	312.8	264.6(m)	228.2(m)	—	1.3
$LaCl_3$	1 071.4	(144.4)	999.8	954.2	841.1	757.4(m)	—	8
LaI_3	657.3	214.7	680.8	632.2	519.2	423(m)	—	18.8
LiF	617.5	35.6	589.1	565.6	521.2	518.1(m)	—	8
LiCl	405.7	59.0	381.4	364.3	323.6(m)	288.5(m)	—	8
LiBr	349.2	—	340.8	324.1	283.9	255.8(m)	—	8
LiI	271.3	—	279.7	265.0	227.8	201.8(m)	—	8
MgF_2	1 113.7	57.4	1 068.1	1 034.6	949.6	—	—	8
$MgCl_2$	642.3	89.6	591.6	559.8	484.8(m)	421.6(m)	349.6(g)	6.3
$MgBr_2$	524.5	117.2	509.4	473.1	404.4(m)	360(m)	—	13
MgI_2	360.1	129.8	377.6	347.5	289.7(m)	242.0(m)	—	13
MnF_2	795.5	93.16	754	724	657	611(m)	—	25
MnF_3	996.5	—	—	—	—	—	—	29
$MnCl_2$	482.3	118.28	442.5	417.0	360.9(m)	324.9(m)	—	6.3
$MnBr_2$	385.1	138.1	373.0	336.2	273.4(m)	231.5(m)	—	8
MnI_2	242.8	—	262.9	233.6	172.9(m)	131.0(m)	—	13
MoF_6	1 559.6(g)	350.6(g)	1 473.4	—	—	—	—	8
$MoCl_5$	527.4	238.6	—	—	—	—	—	10.5

Table 8.8g HALIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
NaF	575.6	51.5	542.1	521.6	469.3	—	—	4
NaCl	412.8	72.9	384.8	365.1	315.7	253.7	—	2
NaBr	361.95	86.9	351.4	333.6	288.3	259.8(m)	—	4
NaI	288.0	98.4	295.2	276.3	232.8(m)	202.2(m)	—	7
NbF_5	1 814.7	160.4	1 702	—	—	—	—	50
$NbCl_2$	407.4	117	—	—	—	—	—	8
$NbCl_{2.67}$	538.4	(137.3)	—	—	—	—	—	8
$NbCl_{3.13}$	601.2	(151.6)	—	—	—	—	—	8
$NbCl_4$	695.0	(184.2)	—	—	—	—	—	—
$NbCl_5$	797.6	(226)	—	—	—	—	—	—
$NbBr_5$	556.4	(306)	—	—	—	—	—	8
$NdCl_3$	1 028.3	—	957.9	913	808	729(m)	—	8
NdI_3	628.9	—	652.3	603	490	394(m)	—	13
NiF_2	657.2	73.7	612.3	582	515	452	—	6.3
$NiCl_2$	305.6	97.76	259.2	232.4	163.7	109.7	—	2.1
$NiBr_2$	212.2	136.0	202.2	174.2	100.9	71.6	—	8
NiI_2	78.3	154.0	116.4	87.1	9.6	−15.5(m)	—	8
NpF_3	1 507.2	118.5	—	—	—	—	—	33
$NpCl_3$	904.3	160.3	—	—	—	—	—	21
$NpCl_4$	199.7	—	—	—	—	—	—	21
PF_3	920.9	272.9(g)	—	—	—	—	—	33
PCl_3	321(m)	218.1(m)	—	—	—	—	—	3.3
PCl_3	288(g)	312.3(g)	268.7(g)	254.4(g)	—	—	—	4
PCl_5	367.1(g)	364.6(g)	294.5(g)	—	—	—	—	13
PBr_3	132.3(g)	348.8(g)	—	—	—	—	—	13
PI_3	18.0(g)	374.6(g)	—	—	—	—	—	21
PbF_2	677.3	161.5	630.8	597.8	530.8	463.8	—	5
PbF_4	930.7	—	845.3	791	—	—	—	18.8
$PbCl_2$	359.2	136.5	312.8	284.5	220.6	196.8	—	2
$PbBr_2$	277.6	161.6	263.8	234.9	171.2(m)	—	—	4
PbI_2	175.4	176.7	195.1	166.2	111.4	—	—	8.3
$PdCl_2$	180.0	103.8	138	105	25	—	—	13
$PdBr_2$	103.4	—	93.8	64.9	—	—	—	21
$PrCl_3$	1 057.4	(144.4)	985.2	940.4	833.6	754.0(m)	—	2
PrI_3	654.7	235.3	679.7	631.2	520.7	424.2	—	18.8
$PtCl_2$	110.9	(129.8)	69.9	41.0	−29	—	—	13
$PtCl_4$	236.9	(205.1)	152	100.0	—	—	—	17
$PtBr_2$	80.4	(154.9)	—	—	—	—	—	13
$PtBr_4$	140.7	(251.2)	117	63	—	—	—	17
PtI_2	16.7	—	—	—	—	—	—	13
PtI_4	72.9	(281.3)	97.1	15.5	—	—	—	33
PuF_3	1 553.0	113.0	—	—	—	—	—	17
$PuCl_3$	949.4	164.1	—	—	—	—	—	4
$PuBr_3$	831.9	191.3	—	—	—	—	—	4
RbF	553.4	73.7	527.7	508.4	466.3(m)	427.4(m)	—	8
RbCl	430.8	91.7	403.2	383.9	335.8(m)	298.5(m)	—	8
RbBr	389.4	108.9	378.5	360.9	316.9(m)	279.3(m)	—	8
RbI	328.7	118.1	334.5	317.4	273.0(m)	235.3(m)	—	8
ReF_6	1 163.9(m)	—	1 068(m)	—	—	—	—	50
$ReCl_3$	263.8	—	200.1	157.4	—	—	—	13
$ReBr_3$	164.5	—	145.7	101.7	—	—	—	2
RhCl	83.7	83.7	66.2	56.5	21	—	—	13
$RhCl_2$	163.3	121.4	123.1	94.2	29	—	—	13
$RhCl_3$	275.4	123.9	—	—	—	—	—	25
$RhBr_3$	209.3	188.4	—	—	—	—	—	25

Table 8.8g HALIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1 227°C	$-\Delta G_{2000}$ 1 727°C	*Accuracy* ±kJ
$RuCl_3$	253.3	127.7	182.1	136.1	26.4	—	—	13
$RuCl_4$	93.4(g)	374.7(g)	64.9(g)	45.6(g)	−5.0(g)	—	—	17
SbF_3	915.9	127.2	860.5	818.5	—	—	—	21
$SbCl_3$	382.7	187.1	—	297.7	—	—	—	2.1
$SbCl_5$	438.8(m)	—	357.1(m)	306.9(m)	—	—	—	13
$SbBr_3$	260.0	210.1	249.5	228.6(m)	—	—	—	38
SbI_3	100.5	215.5	133.6	111.0	—	—	—	33
ScF_3	1 658	90	—	—	—	—	—	50
$ScCl_3$	900.2	—	828.6	782.9	670	586(m)	—	50
$ScBr_3$	711.8	—	686.2	638.5	531.7	450.1(m)	—	50
SeF_6	1 117.4(g)	314.4(g)	1 014(g)	—	—	—	—	5
$SeCl_4$	188.4	194.6	—	—	—	—	—	6.3
SiF_4	1 607.7(g)	282.2(g)	—	—	—	—	—	25
$SiCl_2$	162.4(g)	282.0(g)	—	—	—	—	—	5
$SiCl_4$	695.8(m)	239.9(m)	598.3(m)	571.9(m)	—	—	—	8
$SiBr_4$	461.7(m)	279.6(m)	435(m)	389(m)	—	—	—	29
SiI_4	199.2	265.6	—	—	—	—	—	6
$SmCl_2$	818.9	—	—	—	—	—	—	4.6
$SnCl_2$	350.0	—	309.8	283.0	230.7(g)	—	—	6.3
$SnCl_4$	529.1(m)	258.7(m)	473.9(m)	436.3(g)	360.9(g)	—	—	6.3
$SnBr_2$	266.3	—	256.7	229.9	—	—	—	17
$SnBr_4$	348.2(g)	412.8(g)	322.6(g)	—	—	—	—	11
SnI_2	144.0	167.8	165.4	136.9	—	—	—	21
SrF_2	1 217.7	82.2	—	—	—	—	—	5
$SrCl_2$	829.0	114.9	780.8	755.7	686.6	628	—	5
$SrBr_2$	716.4	143.6	699.2	667.8	597.0	539.7	—	5
SrI_2	563.1	159.1	580.3	548.9	486.9	428.3	—	5
$TaCl_3$	553.5	(155)	—	—	—	—	—	—
$TaCl_4$	708.8	(193)	—	—	—	—	—	—
$TaCl_5$	860.4	(235)	—	—	—	—	—	—
$TaBr_5$	602.9	(306)	—	—	—	—	—	13
TeF_6	1 318.8(g)	337.9(g)	1 223	1 164	—	—	—	5
$TeCl_4$	324.0	200.9	—	—	—	—	—	10.5
$TeBr_4$	195.1	243.6	2 017.2	1 955.1	—	—	—	13
ThF_4	2 112.2	142.14	2 017.2	1 955.1	—	—	—	13
$ThCl_4$	1 187.1	190.5	1 095.7	1 032.0	879	—	—	4
$ThBr_4$	966.1	228.1	933	870.2	721.6	—	—	7
ThI_4	665	—	—	—	—	—	—	50
TiF_3	1 436.2	87.9	—	—	—	—	—	—
TiF_4	1 650.1	131.1	—	—	—	—	—	—
$TiCl_2$	515.7	87.4	—	—	—	—	—	—
$TiCl_3$	722.1	139.8	—	—	—	—	—	—
$TiCl_4$	804(m)	252(m)	—	—	—	—	—	—
$TiBr_2$	407.4	119.7	—	—	—	—	—	—
$TiBr_3$	550.2	171.7	—	—	—	—	—	—
$TiBr_4$	619.6	239.5	—	—	—	—	—	—
TiI_2	241.1	138.1	—	—	—	—	—	—
TiI_4	375.9	246.1	—	—	—	—	—	—
TlF	325.6	95.7	286.6	272.1	251.2	228.2	—	5
TlF_3	573.2	—	—	—	—	—	—	13
TlCl	205.2	113.0	185.1	170.4	150.7(m)	—	—	1.7
$TlCl_3$	315.2	152.4	—	—	—	—	—	13
TlBr	172.5	125.2	169.2	156.2	136.1(m)	—	—	2.9
TlI	124.3	127.7	137.3	123.5	102.6(m)	—	—	2.5
UF_4	1 884	151.9	1 793.2	1 736.7	1 595.6	1 464.1	—	25
UF_5	2 057.8	188.4	—	—	—	—	—	25

Table 8.8g HALIDES—*continued*

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	$-\Delta G_{2000}$ 1 727 °C	*Accuracy* ±kJ
UF_6	2 189.7	227.8	—	1 999.2(g)	—	—	—	25
UCl_3	893.9	159.1	827.7	785.0	678.3	—	—	13
UCl_4	1 051.7	198.5	962.5	904.3	773.3(m)	—	—	8
UCl_5	1 094.8	(243)	—	—	—	—	—	13
UCl_6	1 133.4	285.9	—	—	—	—	—	21
UBr_3	721.4	(188)	695.4	651.0	541.4	—	—	17
UBr_4	826.9	—	794.2	734.8	606.2(m)	—	—	13
UI_3	478.1	(239)	—	—	—	—	—	8
UI_4	529.6	—	565.2	512.9	410(m)	—	—	17
VF_4	1 404.0	121.4	—	—	—	—	—	13
VF_5	1 481.0(m)	209.3(m)	—	—	—	—	—	25
VCl_3	561.0	—	—	—	—	—	—	13
VCl_4	570.2(m)	235.3(m)	498.2(m)	—	—	—	—	13
VBr_2	347.5	125.6	—	—	—	—	—	25
VBr_3	447.9	142.4	—	—	—	—	—	25
VBr_4	393.6(g)	334.9(g)	—	—	—	—	—	25
VI_2	263.8	(147)	—	—	—	—	—	25
VI_3	280.5	(203.1)	—	—	—	—	—	25
WF_6	1 748.3(m)	(251.2)	1 643.7	—	—	—	—	29
WCl_6	414	(217)	310	211.9	100(g)	8(g)	−88(g)	29
YCl_3	974.3	(136.9)	907.7	863.3	769.1	685.4	—	13
YI_3	618.2	(207)	640.4	588.9	490.0	383.8(m)	—	42
$YbCl_2$	800.0	130.6	—	—	—	—	—	13
ZnF_2	764.9	73.7	721.0	700.0	622.6	—	—	13
$ZnCl_2$	416.6	108.4	369.7	339.1	278.8(m)	338.7(g)	—	1.3
$ZnBr_2$	327.8	136.9	313.6	284.7	237.4	—	—	2.1
ZnI_2	209.3	161.2	231.1	201.4	153.7	—	—	1.7
ZrF_4	1 912.5	104.7	1 820.0	—	—	—	—	13
$ZrCl_4$	982.6	186.3	893.0	835.3	—	—	—	4
$ZrBr_4$	760.3	—	—	—	—	—	—	8
ZrI_4	485.3	—	—	—	—	—	—	8

Table 8.8h SILICATES AND CARBONATES

Heats and free energies of formation from the constituent oxides in kJ and standard entropies.
The standard state of carbon dioxide is the perfect gas under 1 atm pressure; that of silica is quartz.

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	*Accuracy* ±kJ
Ag_2CO_3	81.2	167.5	30.6	−2.9	—	—	13
Al_2SiO_5 (kyanite)	8.4	83.7	—	—	—	—	5
(andalusite)	5.9	99.4	—	—	—	—	5
(sillimanite)	3.0	96.3	—	—	—	—	5
$Al_6Si_2O_{13}$ (mullite)	17.2	275.0	—	—	—	—	3
$BaCO_3$ (witherite)	269.4	112.2	214.9	183.1	97.3	—	17
$BaSiO_3$	159.1	—	112.2	112.2	111.8	111.8	13
Ba_2SiO_4	270.0	—	270.0	270.5	—	—	13
Be_2SiO_4	19.7	64.5	—	—	—	—	3
$CaCO_3$ (calcite)	179.2	92.9	131.0	98.8	18.4	—	8
$CaSiO_3$ (wollastonite)	90.0	82.1	89.2	89.2	88.8	88.3	2.1
Ca_2SiO_4	136.9	120.6	128.1	128.9	131.5	134	6.3
Ca_3SiO_5	113.0	168.7	117.2	118.9	122.7	—	8
$CdCO_3$	98.8	—	48.1	14.6	—	—	13
$CoCO_3$	78.9	88.7	—	—	—	—	21
$CuCO_3$	47.5	87.9	—	—	—	—	4

Table 8.8h SILICATES AND CARBONATES—*continued*

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1227 °C	*Accuracy* ±kJ
$FeCO_3$ (siderite)	82.7	92.9	35.6	−0.4	—	—	13
Fe_2SiO_4 (fayalite)	34.3	145.3	—	—	25.1	18.0(m)	13
K_2CO_3	393.7	155.6	342.9	308.6	224.8	—	10
K_2SiO_3	274.2	169.6	260.8	260.4	259.6	—	13
$K_2Si_4O_9$	307.4	265.8	—	—	—	—	13
$K_2Si_2O_5$	299.3	182.1	—	—	—	—	13
Li_2CO_3	226.7	90.2	—	—	37.7	—	15
Li_2SiO_3	139.8	80.4	—	—	—	—	13
$MgCO_3$	117.0	65.7	66.6	32.7	−52.3	—	17
Mg_2SiO_4 (forsterite)	63.2	95.2	63.2	63.2	63.2	63.2	6.3
$MgSiO_3$ (clinoenstatite)	36.4	67.8	36.0	34.8	32.7	30.6	4
$MnCO_3$	116.8	85.8	60.3	22.6	—	—	8
Mn_2SiO_4 (tephroite)	47.3	—	—	—	—	—	8
$MnSiO_3$ (rhodonite)	24.7	89.2	20.9	18.4	12.1	5.9	4
Na_2CO_3	322.0	136.1	280.9	253.7	185.9	—	17
Na_4SiO_4	360.0	195.9	316.9	319.5	325.3	—	25
Na_2SiO_3	232.4	113.9	232.4	232.8	233.2	233.6	33
$Na_2Si_2O_5$	230.6	165.0	233.5	235.2	—	—	13
$NiCO_3$	46.9	85.4	—	—	—	—	13
$PbCO_3$ (cerussite)	87.29	131.0	42.3	12.1	—	—	13
Pb_2SiO_4	16.7	186.7	—	23.4	30.1	39.7	9
$PbSiO_3$	17.6	109.7	—	18.0	19.2	26.4	4
Rb_2CO_3	404.9	—	—	—	—	—	29
$SrCO_3$	234.9	97.1	183.4	149.1	63.6	−22.2	17
$SrSiO_3$	130.6	—	—	—	—	—	4
Sr_2SiO_4	209.3	—	—	—	—	—	8
$ZnCO_3$	70.8	82.5	18.4	−16.7	—	—	4
Zn_2SiO_4	32.6	131.5	31.8	31.4	31.1	28.8	8
$ZrSiO_4$	24.0	84.6	—	—	—	—	13

Table 8.8i COMPOUND (DOUBLE) OXIDES
Heats and free energies of formation from the constituent oxides in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1227 °C	*Accuracy* ±kJ
Al_2TiO_5	8.4	109.7	10.9	12.6	16.7	20.9	8
$BaAl_2O_4$	100.5	148.6	108.7	114.2	127.8	141.6	7
$Ba_3Al_2O_6$	188.4	—	—	—	—	—	9
BaH_2O_3	128.5	122.4	126.3	124.7	121.0	115.2	17
$BaMoO_3$	208.5	144.5	207.4	206.6	204.6	—	11
$BaUO_4$	205.1	168.7	204.9	204.8	204.6	204.3	18
$BeAl_2O_4$	13.0	66.3	13.5	13.8	14.5	15.3	13
CaV_2O_6	143.6	179.2	146.2	148.0	152.4	(156.8)	3
$Ca_2V_2O_7$	262.5	220.6	265.6	267.8	273.0	(240.3)	3
$Ca_3V_2O_8$	322.3	275.0	329.8	334.8	347.4	(314.7)	3
$Ca_3Al_2O_6$	8.4	205.5	18.9	25.9	43.6	61.1	5
$CaAl_2O_4$	15.0	114.1	22.0	26.6	38.2	49.8	3
$CaAl_4O_7$	12.6	177.9	23.4	30.6	48.6	66.6	3
$CaTiO_3$	80.8	93.8	81.9	82.6	84.4	86.2	5
$Ca_3Ti_2O_7$	209.3	234.8	213.7	216.7	224.1	231.5	50
$Ca_4Ti_3O_{10}$	297.2	328.6	362.7	306.4	315.7	324.9	50
$CaZrO_3$	30.6	93.8	31.6	32.3	33.9	35.5	10
$CaHfO_3$	31.4	100.5	31.8	32.0	32.6	33.2	20
$CaMoO_4$	166.6	122.6	168.1	169.1	171.6	(150.0)	5
$CaWO_4$	146.1	126.4	149.3	151.5	156.8	162.1	11

Table 8.8i COMPOUND (DOUBLE) OXIDES—*continued*

Compound	$-\Delta H_{298}$ 25 °C	S_{298} 25 °C	$-\Delta G_{300}$ 27 °C	$-\Delta G_{500}$ 227 °C	$-\Delta G_{1000}$ 727 °C	$-\Delta G_{1500}$ 1 227 °C	*Accuracy* ±kJ
$CaUO_4$	135.6	143.2	137.0	137.9	140.2	142.5	20
$CaFe_2O_5$	40.2	188.8	48.3	53.8	67.4	81.0	5
$Ca_2Fe_2O_4$	20.9	145.2	36.5	46.8	72.8	98.8	11
$CaSnO_3$	72.8	83.7	70.3	68.6	64.4	60.2	3
Ca_2SnO_4	71.6	128.3	70.5	69.8	68.0	66.2	3
$CaTiO_3$	27.6	105.1	27.6	27.6	27.5	27.4	2
$CdAl_2O_4$	−15.1	125.2	−9.3	−5.5	4.1	13.7	5
$CdWO_4$	79.1	154.9	86.3	92.1	103.2	115.3	8
$CeAlO_3$	(13.6)	106.7	15.4	16.5	19.6	22.5	15
$CoTiO_3$	24.7	96.9	22.8	21.5	18.3	15.1	5
$CoWO_4$	62.0	126.4	61.3	60.7	59.5	58.3	5
$CoAl_2O_4$	33.5	99.6	32.3	31.3	29.1	26.9	5
$CoCr_2O_4$	59.9	126.8	57.7	56.2	52.6	48.9	3
$CoFe_2O_4$	27.6	142.7	28.3	28.8	29.9	30.1	3
$CuAlO_2$	11.9	67.0	10.4	9.4	6.8	4.3	3
$CuAl_2O_4$	−18.4	111.3	−13.1	−9.6	−0.8	8.0	3
$CuGaO_2$	7.1	83.3	5.4	4.3	1.5	—	3
$CuGa_2O_4$	−17.2	146.5	−11.5	−7.7	1.8	10.3	3
$CuFeO_2$	36.4	88.9	36.2	35.7	35.0	34.3	10
$CuFe_2O_4$	−10.0	146.4	(−5.0)	(−1.7)	6.6	14.9	10
$CuCr_2O_4$	−3.1	129.8	(−1.3)	(−0.2)	2.8	5.7	3
$FeTiO_3$	29.7	105.9	28.7	28.1	26.4	24.8	5
$FeAl_2O_4$	27.8	106.7	26.9	26.2	24.5	22.9	2
Fe_2ZnO_4	5.0	134.9	6.1	6.8	8.6	10.4	5
$FeMoO_4$	54.4	129.3	52.2	50.8	47.1	(20.0)	20
$FeWO_4$	75.3	131.9	74.4	73.9	72.4	71.0	13
Fe_2NiO_4	22.6	126.0	22.7	22.8	23.0	23.2	10
Fe_2CoO_4	27.6	142.7	28.3	28.7	29.9	31.0	5
$FeCr_2O_4$	52.1	146.9	54.1	55.6	58.0	61.5	3
FeV_2O_4	24.3	157.0	24.3	24.3	24.3	—	3
Li_2TiO_3	129.3	91.7	130.3	132.0	132.7	—	12
$LiAlO_2$	54.0	53.2	56.8	58.3	62.6	66.9	7
$LiFeO_2$	17.8	75.3	21.6	24.1	30.4	36.7	3
Mg_2TiO_4	—	103.8	—	—	—	—	—
$MgTiO_3$	23.0	74.5	22.2	21.6	20.2	18.8	3
$MgTi_2O_3$	—	127.3	—	—	—	—	—
$MgAl_2O_4$	35.6	80.6	36.4	36.9	38.2	39.5	3
$MgFe_2O_4$	15.5	123.9	18.3	20.8	25.5	30.2	3
$MgMn_2O_4$	11.3	—	—	—	—	—	—
$MgCr_2O_4$	41.9	105.9	41.2	40.7	39.6	38.5	5
$MgMoO_4$	54.0	118.9	58.2	61.0	68.1	(61.0)	5
$MgWO_4$	73.3	100.9	72.7	72.1	71.3	70.3	3
$Mg_2V_2O_7$	81.8	200.1	86.5	89.6	97.4	105.2	3
MgV_2O_6	49.2	160.7	50.3	51.0	52.8	—	3
$MnAl_2O_4$	37.7	103.8	35.5	34.2	30.6	27.1	5
$MnCr_2O_4$	69.1	134.0	67.0	65.6	62.0	58.5	5
$MnMoO_4$	61.1	136.0	60.6	60.3	59.5	(52.0)	12
Na_2TiO_3	213.5	121.8	212.4	211.7	209.9	(206.0)	20
$Na_2Ti_2O_5$	232.3	173.7	231.7	232.3	230.2	(224.0)	25
$Na_2Ti_3O_7$	237.3	234.0	239.7	241.2	246.1	(247.0)	25
$NaAlO_2$	87.5	70.7	89.8	91.3	95.2	99.0	5
Na_2CrO_4	334.5	185.9	346.1	353.9	373.3	392.6	14
$NaCrO_2$	101.5	83.3	103.0	103.1	106.6	109.4	2.5
$NaFeO_2$	44.0	88.3	46.1	47.5	51.0	54.5	10
Na_2MoO_4	306.0	159.5	308.0	309.3	312.6	(315.9)	50

Table 8.8i COMPOUND (DOUBLE) OXIDES—*continued*

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	$-\Delta G_{300}$ 27°C	$-\Delta G_{500}$ 227°C	$-\Delta G_{1000}$ 727°C	$-\Delta G_{1500}$ 1227°C	*Accuracy* ±kJ
$NaVO_3$	162.0	113.9	165.3	167.5	173.0	—	8
$Na_4V_2O_7$	534.6	318.6	545.9	553.5	572.4	—	18
Na_3VO_4	357.5	189.6	361.0	363.3	369.2	—	13
$NiAl_2O_4$	6.1	98.4	8.9	10.7	15.3	19.9	2
$NiTiO_3$	18.0	80.2	15.5	13.9	9.7	5.6	9
$NiWO_4$	45.2	118.0	46.5	47.3	49.4	51.6	9
$NiCr_2O_4$	13.6	124.3	15.1	16.1	18.6	21.1	5
$NiGa_2O_4$	4.4	130.2	6.6	8.1	11.8	15.7	2
$PbTiO_3$	34.6	112.0	33.2	32.4	29.9	27.5	20
$Pb_2V_2O_7$	146.9	—	—	—	—	—	7
$Pb_3V_2O_8$	170.8	—	—	—	—	—	9
$PbMoO_4$	41.9	166.2	48.5	52.9	63.9	—	15
$PbWO_4$	58.6	167.4	66.1	71.2	83.8	96.4	9
$SrTiO_3$	134.0	108.4	134.8	135.3	136.5	138.8	4
Sr_2TiO_4	159.1	159.1	158.4	157.9	156.7	155.5	9
$SrHfO_3$	78.3	113.0	77.7	77.3	76.3	75.3	20
$SrAl_2O_4$	16.6	108.8	17.3	17.7	18.8	19.9	25
$SrMoO_4$	212.2	128.9	210.9	210.0	207.8	—	9
$SrWO_4$	186.3	134.0	187.0	187.5	188.8	190.0	20
Zn_2TiO_4	3.3	148.2	3.6	8.8	13.8	—	3
$ZnTiO_3$	6.7	95.0	7.0	7.2	7.7	—	3
$ZnFe_2O_4$	5.0	134.9	6.1	6.8	8.6	10.4	5
$ZnWO_4$	41.9	144.4	49.3	54.3	66.7	79.1	3
$ZnAl_2O_4$	45.0	87.1	42.7	41.2	37.3	33.5	2
$ZnCr_2O_4$	62.8	116.4	60.3	58.6	54.3	50.1	2

Table 8.8j PHOSPHIDES
Heats of formation in kJ and standard entropies

Compound	$-\Delta H_{298}$ 25°C	S_{298} 25°C	*Accuracy* ±kJ	*Compound*	$-\Delta H_{298}$ 25°C	S_{298} 25°C	*Accuracy* ±kJ
AgP_2	44.8	87.9	9	InP	75.3	59.8	9
AgP_3	69.1	105.5	11	Mg_3P_2	464.6	77.4	80
AlP	164.5	47.3	3	MnP	96.3	52.3	17
Au_2P_3	97.5	150.7	15	MnP_3	174.1	96.7	31
Ca_3P_2	506.5	123.9	25	Ni_3P	200.2	106.3	11
Co_2P	157.5	77.4	15	Ni_5P_2	391.4	185.0	19
CoP	125.6	50.2	21	Ni_2P	164.5	77.4	18
CoP_3	204.7	98.4	21	Ni_6P_5	556.3	276.3	60
Cu_3P	129.0	119.3	18	NiP_2	129.3	73.3	15
CuP_2	90.1	81.6	11	NiP_3	157.8	98.4	17
Fe_3P	164.1	101.7	9	SiP	62.0	32.7	15
Fe_2P	160.3	72.4	9	ThP	361.3	70.3	40
Fe_1P	138.1	—	13	Th_3P_4	1195.1	247.0	110
FeP_2	221.0	—	17	Zn_3P_2	159.0	150.7	18
GaP	122.2	52.3	9	ZnP_2	101.7	60.3	13
GeP	27.2	61.1	11				

The standard state is white phosphorus and for P white → P red, $\Delta H = -17.4$ kJ g-atom^{-1}. With respect to red phosphorus, heats of formation are thus less negative per g-atom P by this amount.

Table 8.9a PHOSPHIDES
Dissociation pressures in mmHg*

Dissociating phase	*Other condensed phase*	*Temp. °C*	*Phosphorus pressure* mmHg		
			p_{P_2}	p_{P_4}	Σp
$AgP_3(s)$	$AgP_2(s)$	411–501		$\log p = -\frac{7766}{T} + 12.74$	
$AgP_2(s)$	Ag(s)	420–506		$\log p = -\frac{7186}{T} + 11.60$	
$Au_2P_3(s)$	Au(s)	501–700		$\log p = -\frac{9124}{T} + 12.21$	
$CoP_3(s)$	CoP(s)	934	15	27	42
		994	54	113	167
		1037	120	280	400
CoP(s)	$Co_2P(s)$	1215	—	—	24
$CuP_2(s)$	$Cu_3P(s)$	632	—	—	18
		672	—	—	65
		712	—	—	200
		762	—	—	698
$FeP_2(s)$	FeP(s)	892	16.5	78.5	95
		922	34	166	200
		953	63	329	392
		973	92	516	608
FeP(s)	$Fe_2P(s)$	1175	12.5	—	13
		1215	25.5	—	27
GeP(s)	Ge(s)	500	—	—	64
		524	—	—	156
		559	—	—	394
$MnP_3(s)$	MnP(s)	580–680		$\log p = -\frac{11856}{T} + 14.948$	
$NiP_3(s)$	$NiP_2(s)$	597	—	135	135
		644	—	460	460
		667	—	850	850
$NiP_2(s)$	$Ni_6P_5(s)$	740	4	109	113
		761	7	193	200
		780	11	323	334
		804	19	585	604
$Ni_6P_5(s)$	$Ni_2P(s)$	742	2	27	29
		761	3	43	46
		780	5	75	80
		806	11	172	183
		823	16	262	278
$OsP_2(s)$	Os(s)	1190	—	—	8
$ReP_3(s)$	$ReP_2(s)$	863	11	57	68
		904	31	186	217
		935	63	430	493
		956	101	762	863
$ReP_2(s)$	ReP(s)	935	19	39	58
		986	52	120	172
		1028	111	278	389
		1059	187	494	681
ReP(s)	Re(s)	1110	8.5	—	9
		1141	14	—	15
		1172	23	—	24.5
		1214	43	—	46.5

*To convert the pressures given in mmHg to pascals multiply by 133.322.

Table 8.9a PHOSPHIDES—*continued*

Dissociating phase	*Other condensed phase*	*Temp.* °C	*Phosphorus pressure* mmHg		
			p_{P_2}	p_{P_4}	Σp
$RhP_3(s)$	$RhP_2(s)$	968	19	22	41
		1 012	39	45	84
		1 038	59	71	130
		1 067	98	125	223
$RuP_2(s)$	RuP(s)	1 190	34	—	34
SiP(s)	$SiP_{0.2}(s)$	1 010	33	34	67
		1 055	76	86	162
		1 068	96	115	211
		1 101	169	220	389
$TaP_2(s)$	TaP(s)	787	7	111	118
		816	14	221	235
		836	23	397	420
		846	29	494	523
$VP_2(s)$	VP(s)	657	—	148	148
		670	—	195	195
		680	—	298	298
		689	—	402	402
$WP_{0.96}$	$WP_{0.65}$	750	1.65×10^{-5}	—	1.65×10^{-5}
		850	4.6×10^{-4}	—	4.6×10^{-4}
		950	7.2×10^{-4}	—	7.2×10^{-4}
$ZrP_2(s)$	ZrP(s)	729	2	26	28
		774	5	74	79
		814	12	165	177
		848	25	357	382

Ref. 5.
*To convert the pressures given in mmHg to pascals multiply by 133.322.

Table 8.9b SULPHIDES
Dissociation pressures in mmHg‡
A = Dissociating phase. *B* = Other condensed phase.

Phases	*Temp.* °C	*Vapour pressure* mmHg		*Phases*	*Temp.* °C	*Vapour pressure* mmHg	
		p_{S_2}	Σp			p_{S_2}	Σp
A $As_2S_2(g)$	755–1 075	$\log K_p = \log \frac{p_{S_2}^4 \cdot p_{As_4} \cdot p_{As_2} \cdot p_{As}^2}{p_{As_2S_2}^4}$		*A* $CoS_{1.3}(s)$	700	—	31
					730	—	79
					760	—	162
		$= -\frac{312\,900}{T} + 56.7$		*A* CuS(s)	460	19	90
				B $Cu_2S(s)$	474	34	210
A $CcS_{1.92}(s)$	700	—	38	*A* $FeS_{1.94}(s)$	629	—	66
	730	—	97	*B* $FeS_{1.12}(s)$	649	—	170
	760	—	226		659	—	258
					669	—	445
A $CoS_{1.5}(s)$	700	—	40				
	730	—	86	*A* $Ir_3S_8(s)$	880	—	400
	760	—	200	*B* $IrS_2(s)$	—	—	—

Table 8.9b SULPHIDES—*continued*

Phases	*Temp.* °C	*Vapour pressure* mmHg p_{S_2}	Σp
A IrS_2(s)	880	—	52
B Ir_2S_3(s)	904	—	75
	944	—	153
A Ir_2S_3(s)	1 020	—	55
B Ir(s)	1 056	—	109
	1 073	—	148
A MnS_2(s)	408	—	424
B MnS(s)	—	—	—
A NiS_2(s)	650	—	42
	700	—	153
	730	—	325
	760	—	650
A OsS_2(s)	944	—	22
	994	—	85
B Os(s)	1 044	—	214
	1 094	—	490
A PdS_2(s)	451	16	88*
B PdS(s)	476	35	210*
	501	72	425*
A PtS_2(s)	616	—	38
B PtS(s)	651	—	98
	691	—	240
A PtS(s)	1 060	30	30
B Pt(s)	1 110	75	75
	1 186	249	249
A ReS_2(s)	1 110	13	13
B Re(s)	1 189	55	55
	1 225	96	96
A Rh_2S_5(s)	715	—	44
	757	—	130
B Rh_2S_3(s)	790	—	300
	830	—	610

Phases	*Temp.* °C	*Vapour pressure* mmHg p_{S_2}	Σp
A Rh_2S_3(s)	953	—	19
	1 003	—	56
B Rh_3S_4(s)	1 043	—	137
	1 083	—	300
A Rh_3S_4(s)	953	—	8
	1 003	—	24
B Rh_9S_8(s)	1 043	—	54
	1 083	—	120
A RuS_2(s)	1 123	3.0	3.0
	1 153	5.3	5.3
B Ru(s)	1 184	9.7	9.7
	1 208	15.3	15.3
A Th_3S_7(s)	651	—	43
	676	—	87
B ThS_2(s)	713	—	163
	754	—	381
A TiS_3(s)	500	38.5	91†
	525	83	223†
B TiS_2(s)	538	122	349†
	551	173	429
A US_3(s)	500	—	~2
	608	—	34
B US_2(s)	650	—	155
	700	—	470
A VS_4(s)	390	—	48
B V_2S_3(s)	412	—	131
	440	—	350
A $ZrS_{1.6}$(s)	783	52	52
	814	98	98
B ZrS_2(s)	847	187	187
	874	311	311

t °C	p_{S_6}	p_{S_8}
451	52	20
476	125	50
501	254	99

t °C	p_{S_6}	p_{S_8}
500	43	9.5
525	112.5	27.5
538	181	46
551	280	76

Ref. 6.

‡To convert the pressures given in mmHg to pascals multiply by 133.322.

8.6 Molar heat capacities and specific heats

Table 8.10 ELEMENTS
Molar heat capacities

The molar heat capacity C_p may be given empirically by an equation of the form:
$C_p = 4.186\,8(a + 10^{-3}bT + 10^{5}cT^{-2})$, $JK^{-1}mol^{-1}$
where a, b and c are constants and T = temperature in K.

The values of the constants are given below.

Element	*a*	*b*	*c*	*Remarks*	*Temp. range* K
Ag(s)	5.09	2.04	0.36		298–m.p.
Ag(l)	7.3	—	—		m.p.– 1 600
Al(s)	4.94	2.96	—		298–m.p.
Al(l)	7.0	—	—		m.p.– 1 273
As(s)	5.54	1.32	—		273–1 090
Au(s)	5.66	1.24	—		298–m.p.
Au(l)	7.0	—	—		m.p.– 1 575
B (amorph.)	3.835	2.39	−1.50		298–1 240
B (cryst.)	4.735	1.38	−2.20		298–1 100
Ba(β)	−1.36	19.2	—		673–m.p.
Ba(l)	10.5		—		m.p.–1 105
Be(s)	4.54	2.12	−0.82		298–1 173
Be(l)	6.08	0.515	—		1 560–2 200
Bi(s)	4.49	5.40	—		298–m.p.
Bi(l)	4.78	1.47	5.05		m.p.–820
Br_2(l)	17.2	—	—		300
Br_2(g)	8.93	0.11	−0.31		298–1 600
C (graph)	0.026	9.307	−0.354	$-4.155 \times 10^{-6}T^2$	298–1 100
	5.841	0.104			1 100–4 000
C (diam)	2.18	3.16	—		298–1 200
Ca(α)	6.064	−1.736	—	$+5.67 \times 10^{-6}T^2$	273–720
Ca(β)	−0.086	9.86	—		720–m.p.
Ca(l)	7.00	—	—		m.p.–1 250
Cd(s)	5.31	2.94	—		298–m.p.
Cd(l)	7.1	—	—		m.p.–1 100
Ce(α)	5.613	2.485		$+0.97 \times 10^{-6}T^2$	298–1 003
Ce(β)	9.05	—	—		1 003–m.p.
Ce(l)	9.35	—	—		m.p.–1 373
Cl_2(g)	8.82	0.06	−0.68		298–3 000
Co(α)	5.11	3.42	−0.21		298–650
Co(β)	3.30	5.86	—		718–1 400
Co(γ)	9.60	—	—		1 400–m.p.
Co(l)	9.65	—	—		m.p.–1 900
Cr(s)	5.84	2.36	−0.88		298–1 823
Cr(l)	9.4	—	—		m.p.
Cs(s)	7.42	—	—		298–m.p.
Cs(l)	7.62	—	—		m.p.–400
Cu(s)	5.41	1.40	—		298–m.p.
Cu(l)	7.5	—	—		m.p.–1 600
F_2(g)	8.29	0.44	−0.80		—
Fe(α, β, δ)	8.873	1.474	—	$-56.92T^{-1/2}$	298–m.p.
Fe(γ)	5.85	2.02	—		1 187–1 664
Fe(l)	10.0	—	—		m.p.–
Ga(s)	6.25	—	—		298–m.p.
Ga(l)	6.65	—	—		295–373
Ge(s)	5.16	1.40	—		298–m.p.
Ge(l)	6.60	—	—		m.p.–1 573
H_2(g)	6.52	0.78	0.12		298–3 000
Hf(s)	5.61	1.82	—		298–1 346
Hg(l)	6.61	—	—		298–b.p.
I_2(s)	9.59	11.90	—		298–387

Table 8.10 ELEMENTS—*continued*

Element	*a*	*b*	*c*	*Remarks*	*Temp. range* K
I_2(l)	19.2	—	—		387–456
I_2(g)	8.89	—	—		456–1 500
In(s)	5.81	2.50	—		298–m.p.
In(l)	7.24	−0.33	—		m.p.–800
Ir(s)	5.56	1.42	—		298–1 800
K(s)	6.04	3.12	—		298–m.p.
K(l)	8.886	−4.57	—	$+2.94 \times 10^{-6} T^2$	m.p.–1 037
La(s)	6.17	1.60	—		298–800
Li(s)	3.33	8.21	—		273–m.p.
Li(l)	5.85	1.31	2.07	$-467 \times 10^{-6} T^2$	m.p.–580
Mg(s)	5.33	2.45	−0.103		298–m.p.
Mg(l)	7.80	—	—		m.p.–1 100
Mn(α)	5.70	3.38	−0.375		298–1 000
Mn(β)	8.33	0.66	—		1 108–1 317
Mn(γ)	6.03	3.56	−0.443		1 374–1 410
Mn(δ)	11.10	—	—		1 410–1 450
Mn(l)	11.0	—	—		m.p.–b.p.
Mo(s)	5.77	0.28	—	$+2.26 \times 10^{-6} T^2$	298–2 500
N_2(g)	6.67	1.0	—		298–2 000
Na(s)	19.71	−88.27	—	$+150 \times 10^{-6} T^2$	273–m.p.
Na(l)	8.965	−4.594	—	$+2.542 \times 10^{-6} T^2$	m.p.–451
Nb(s)	5.66	0.96	—		298–1 900
Nd(α)	3.503	6.434	+1.07		298–1 128
Nd(β)	10.65	—	—		1 128–m.p.
Ni(α)	4.06	+7.04	—		298–630
Ni(β)	6.00	+1.80	—		630–m.p.
Ni(l)	9.20	—	—		m.p.–2 200
O_2(g)	7.16	1.00	−0.40		298–3 000
Os(s)	5.69	0.88	—		298–1 900
P (yell.)	4.57	3.78	—		273–m.p.
P (red)	4.05	3.56	—		298–800
P(l)	6.29	—	—		m.p.–370
Pb(s)	5.63	2.33	—		298–m.p.
Pb(l)	7.75	−0.74	—		m.p.–1 300
Pd(s)	5.80	1.38	—		298–1 828
Pr(α)	6.21	0.3	—		298–1 068
Pr(β)	9.19	—	—	$+3.11 \times 10^{-6} T^2$	1 068–m.p.
Pt(s)	5.80	1.28	—		298–2043
Pu(α)	5.91	5.8			298–395
Pu(β)	5.21	7.05			395–480
Pu(γ)	2.98	11.1			480–588
Pu(δ)	9.0	—	—		588–753
Pu(ε)	8.4	—	—		753–913
Pu(l)	10.0	—	—		913–2 000
Rb(s)	7.27	—	—		298–m.p.
Rb(l)	7.85	—	—		m.p.–373
Re(s)	5.80	0.95	—		298–2 300
Rh(s)	5.49	2.06	—		298–1 900
Ru(α)	5.28	1.1	—		298–2 000
S (rhomb.)	3.58	6.24	—		273–369
S (monocl.)	3.56	6.95	—		273–392
S(l)	5.4	5.5	—		m.p.–b.p.
S_2(g)	8.54	0.28	−0.79		298–2 000
Sb(s)	5.51	1.78	—		273–m.p.
Sb(l)	7.5	—	—		m.p.–1 000
Se(s)	4.53	5.5	—		273–490
Se(l)	7.00	—	—		490–600
Si(s)	5.72	0.59	−0.99		298–1 200
Si(l)	6.12	—	—		m.p.–1 873
Sm(α)	6.00	5.84	−0.61		298–1 190

Table 8.10 ELEMENTS—*continued*

Element	*a*	*b*	*c*	*Remarks*	*Temp. range* K
Sm(β)	11.22	—	—		1 190–1 345
Sm(l)	12.57	—	—		m.p.–1 398
Sn(s)	5.16	4.34	—		298–m.p.
Sn(l)	8.29	−2.2	—		m.p.–800
Ta(s)	6.65	−0.52	−0.45	$+0.47\times10^{-6}T^2$	298–2 300
Te(s)	4.58	5.25	—		273–m.p.
Te(l)	9.0	—	—		m.p.–873
Th(s)	5.63	3.04	—		298–1 300
Ti(α)	5.28	2.4	—		298–1 155
Ti(β)	4.74	1.90	—		1 155–1 350
Tl(α)	3.74	6.04	+0.67		298–506
Tl(β)	5.00	5.00	—		506–m.p.
Tl(l)	7.2	—	—		m.p.–1 760
U(α)	2.61	8.95	1.17		298–941
U(β)	10.0	—	—		941–1 048
U(γ)	9.1	—	—		1 048–m.p.
V(s)	4.90	2.58	+0.2		298–1 900
W(s)	5.74	0.76	—		298–2 000
Y(α)	5.72	1.805	+0.08		298–1 758
Y(β)	8.37	—	—		1 758–m.p.
Y(l)	9.51	—	—		m.p.–1 950
Zn(s)	5.35	2.40	—		298–m.p.
Zn(l)	7.5	—	—		m.p.–b.p.
Zr(α)	5.25	2.78	−0.91		298–1 135
Zr(β)	5.55	1.11	—		1 135–m.p.

Table 8.11 ALLOY PHASES AND INTERMETALLIC COMPOUNDS
Molar heat capacities and specific heats

Generally, Neumann and Kopp's rule applies better to intermetallic compounds than to inorganic salts. Thus, the molar heat capacity of an alloy may be calculated additively from the atomic heat capacities of the components. This relationship is useful as only a few specific heats of alloys have been measured.

In the following cases Neumann–Kopp's rule is obeyed to within ±3% in the temperature range 0–500°C: Ag–Au; Ag_3Al; γ-Ag–Al; β-Ag–Mg; AlCu; Al_2Cu; $AlCu_3$; Al_3Mg_4; Bi–Cd; Co_2Sn; Cu_2Mg; $MgZn_2$; Mg_2Si; Pd–Sb

The heat capacities of heterogeneous alloys must always be calculated additively from those of the components.

In other cases the calculated values differ from the determined values by more than 3%. This result may be due in part to experimental errors.

C_p may be represented empirically by an equation of the form:

$$C_p = 4.1868\,(a + 10^{-3}bT + 10^{5}cT^{-2})\,\mathrm{J\,K^{-1}\,mol^{-1}}$$

where a, b and c are constants and T is the temperature in K. The values of the constants are given below.

Phase	*a*	*b*	*c*	*Temp. range* K
AuCd	7.66	10.36	—	298–900
AuCd (liq.)	14.4	—	—	900–1 100
AuCu		*See* ref. 3		320–900
$AuCu_3$		*See* ref. 3		298–1 200
$AuPb_2$ (liq.)	23.1	—	—	527–800
$AuSb_2(\alpha)$	17.12	4.64	—	298–628
AuSn	11.13	3.8	—	298–691
AuSn (liq.)	14.6	—	—	691–900
AuZn(β)	11.87	2.85	—	723–m.p.
AuZn (liq.)	13.6	—	—	m.p.–1 200

Table 8.11 ALLOY PHASES AND INTERMETALLIC COMPOUNDS—*continued*

Phase	*a*	*b*	*c*	*Temp. range* K
Bi_3Tl_2	31.5	—	—	298–487
Bi_3Tl_2 (liq.)	35.8	—	—	487–700
Cd–Cu		*See* ref. 2		292–373
Cd_3Cu_2 (liq.)	41.5	—	—	835–1 000
Cd_3Mg		*See* ref. 2		298–543
CdMg		*See* ref. 2		298–543
$CdMg_3$		*See* ref. 2		298–543
Co_7W_6	68.86	29.7	—	293–1 145
$Cr_{0.48}Fe_{0.52}(\alpha)$	5.02	2.78	—	1 100–1 400
$Cr_{0.48}Fe_{0.52}$	8.06	—	—	870–1 100
Cu–Ni		79–94% Ni *see Figure 8.1*		
CuPd	12.02	1.96	−1.16	298–1 200
Cu_3Pd	20.98	8.80	−1.16	298–1 200
Cu_2Sb	16.38	6.60	—	298–600
$Cu_3Sb(\beta)$	21.79	9.00	—	273–573
Cu–Zn		*See Figure 8.2*		
Fe_7W_6	72.08	24.0	—	293–1 145
FeW_2	28.29	9.90	−1.60	298–1 250
$MgNi_2$	15.67	7.30	—	298–900
$Ni_3Sn(\delta)$	20.78	10.2	—	273–943
Ni_4W	25.7	11.14	—	293–1 100
$PtSb_2$	15.27	5.06	—	298–900
PtSn	11.26	2.20	—	298–1 400

Cr–Ni. Atomic heats of alloys with 1.8–11 at. % Cr obey Kopp's law above the Curie temperature.

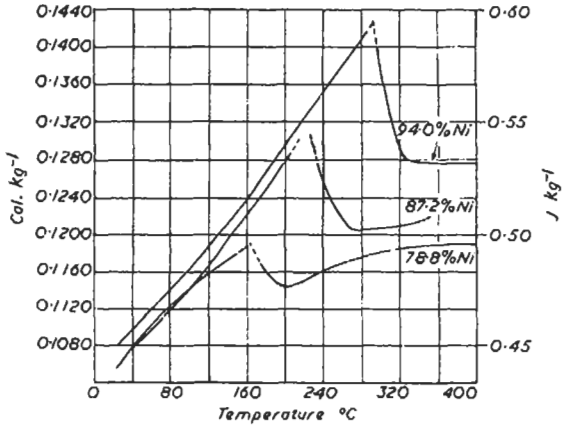


Figure 8.1 *Specific heat of* Cu–Ni *alloys*

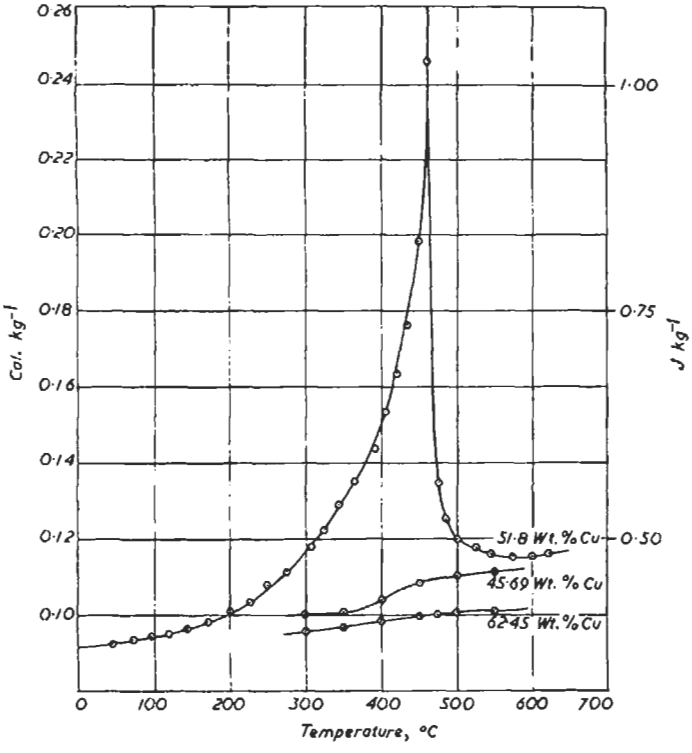


Figure 8.2 *Specific heat of* Cu–Zn *alloys*

Table 8.12a BORIDES
Molar heat capacities

C_p may be represented empirically by an equation of the form:

$C_p = 4.1868\ (a + 10^{-3}bT + 10^{5}cT^{-2})$ J K^{-1} mol^{-1}

where a, b and c are constants and T = temperature in K. The values of the constants are given below.

Boride	*a*	*b*	*c*	*Temp. range* K
CrB	10.12	3.83	−2.40	298–1 200
CrB_2	9.63	10.7	—	298–1 200
Mo_2B	18.42	1.3	—	298–800
MoB	9.77	3.07	−1.13	298–1 200
MoB_2	7.92	(13)	—	600–1 200
NbB_2	11.01	9.38	−1.78	298–1 200
NiB	10.26	3.5	−2.69	298–1 300
Ni_3B_4	37.28	11.74	−9.03	298–1 300
TaB	7.82	5.8	—	500–1 200
TaB_2	14.21	4.49	−3.60	298–3 370
TiB_2	13.48	6.48	−4.17	298–3 190
UB_2	25.58	−9.62	−8.48	298–2 300
W_2B	18.46	1.44	−3.14	298–1 200
WB	13.89	−0.78	−5.02	298–1 200
W_2B_5	39.27	2.08	−16.72	298–1 200
ZrB_2	15.79	4.22	−3.51	298–1 200

Table 8.12b CARBIDES
Molar heat capacities

C_p may be represented empirically by an equation of the form:

$C_p = 4.186\,8(a + 10^{-3}bT + 10^{5}cT^{-2})$ J K^{-1} mol^{-1}

where a, b and c are constants and T = temperature in K. The values of the constants are given below.

Carbide	*a*	*b*	*c*		*Temp. range* K
Al_4C_3	36.97	6.866	−10.02		298–1 800
B_4C	22.99	5.40	−10.72		298–1 100
Be_2C	27.37	3.60	−14.23		430–1 200
$CaC_2(\alpha)$	16.40	2.84	−2.07		298–720
$CaC_2(\beta)$	15.40	2.00	—		720–1 275
Cr_3C_2	30.03	5.58	−7.4		298–1 500
Cr_7C_3	57.00	14.38	−10.1		298–1 500
Cr_4C	29.35	7.40	−5.02		298–1 700
$Fe_3C(\alpha)$	19.64	20.0	—		298–463
$Fe_3C(\beta)$	25.62	3.0	—		463–1 500
CH_4(g)	5.65	11.44	−0.46		298–1 500
$Mn_3C(\alpha)$	25.26	5.60	−4.07		298–1 310
$Mn_3C(\beta)$	38.00	—	—		1 310–1 500
$NbC_{0.5}$	7.94	1.50	−1.025		298–1 703
$NbC_{0.75}$	8.95	2.25	−1.26		298–1 763
NbC	10.79	1.73	−2.15		298–1 790
SiC	12.14	0.47	−11.76	$1.96 \times 10^{6}\,T^{-3}$	298–3 260
Ta_2C	15.88	3.33	−2.05		298–3 775
TaC	10.35	2.71	−2.10		298–4 270
$ThC_{1.94}$	15.17	2.89	−2.21		298–1 700
UC	13.40	1.02	−1.46		298–2 073
U_2C_3	29.9	3.06	−3.71		298–2 050
UC_2	16.5	2.04	−2.25		298–2 050
$VC_{0.88}$	8.69	3.18	−1.7		298–2 000
WC	10.37	2.06	−2.23	$0.24 \times 10^{-6}T^{2}$	298–2 500

Table 8.12c NITRIDES
Molar heat capacities

C_p may be represented empirically by an equation of the form:

$C_p = 4.186\,8\,(a + 10^{-3}bT + 10^{5}cT^{-2})$ J K^{-1} mol^{-1}

where a, b and c are constants and T = temperature in K. The values of the constants are given below.

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
AlN	8.22	4.05	−2.00		298–1 500
BN (hexag.)	16.29	0.675	—	$-854T^{-1/2}$	298–1 400
BN (cubic)	8.10	3.52	−5.51		298–1 200
Be_3N_2	12.89	24.75	−4.22		298–430
Ca_3N_2	33.17	3.70	−6.29		298–1 468
CeN	11.1	1.65	−1.73		298–2 000
Cr_2N	15.24	6.8	—		298–800
CrN	9.84	3.9	—		298–800
Cu_3N	21.7	—	—		298–373
Fe_4N	26.8	8.16	—		298–373

Table 8.12c NITRIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
Fe_2N	14.9	6.1	—		298–373
NH_3	7.11	6.00	−0.37		298–1 800
Li_3N	11.73	23.00	—		298–800
$Mg_3N_2(\alpha)$	22.81	7.30	—		298–823
$Mg_3N_2(\beta)$	29.60	—	—		823–1 061
$Mg_3N_2(\gamma)$	29.54	—	—		1 061–1 300
Mn_4N	21.16	30.5	—		298–800
Mn_3N_2	30.55	38.40	—		298–800
Mn_3N_2	22.32	22.40	—		298–800
Mo_2N	11.19	13.8	—		298–800
NbN	8.69	5.40	—		298–600
Si_3N_4	16.83	23.6	—		298–900
Ta_2N	16.85	4.22	−1.69		298–3000
TaN	13.21	0.65	−3.02		298–3360
ThN	11.34	2.28	−1.14		298–2000
Th_3N_4	27.78	31.8	—		298–800
TiN	11.91	0.94	−2.96		298–1 800
VN	10.94	2.10	−2.21		298–1 611
Zn_3N_2	19.00	22.5	—		298–700
ZrN	11.10	1.68	−1.72		298–1 700

Table 8.12d SILICIDES
Molar heat capacities

C_p may be given empirically by an equation of the form:

$C_p \approx 4.186\ (a + 10^{-3}bT + 10^{3}cT^{-2})$ J K^{-1} mol^{-1}

The values of the constants a, b and c are given below.

Compound	*a*	*b*	*c*	*Temp. range* K
CoSi	11.75	2.89	−1.80	298–1 733
CoSi (liq.)	20.88	—	—	m.p.–1 900
$CoSi_2$	16.935	4.46	−2.37	298–m.p.
$CoSi_2$ (liq.)	27.75	—	—	m.p.–1 900
Cr_3Si_3	47.46	11.78	−6.12	298–1 300
CrSi	12.43	2.09	−2.01	298–1 700
$CrSi_2$	15.68	5.38	−1.855	298–1 730
$CrSi_2$ (liq.)	21.5	—	—	1 730–1 900
FeSi	10.72	4.30	—	298–900
Mg_2Si	17.52	3.58	−2.11	298–873
Mn_3Si	24.11	12.45	−3.52	298–950
Mn_5Si_3	48.13	12.94	−4.68	298–m.p.
MnSi	11.79	3.05	−1.53	298–m.p.
$Mn_{0.37}Si_{0.63}$	6.37	4.085	−1.16	298–1 425
Mo_3Si	20.52	5.42	+0.076	298–2 200
Mo_5Si_3	43.82	8.37	−2.87	298–2 200
$MoSi_2$	16.22	2.86	−1.57	298–2 200
Nb_5Si_3	45.21	7.36	−3.60	298–2 000
$NbSi_2$	15.10	3.67	−0.67	298–2 000
Ni_2Si	15.8	3.29	—	298–1 582

Table 8.12d SILICIDES *continued*

Compound	*a*	*b*	*c*	*Temp. range* K
NiSi	11.65	1.47	−1.56	298–1 265
$Ni_{0.35}Si_{0.65}$	5.98	0.88	−0.86	298–1 200
Re_5Si_3	45.60	10.8	−3.36	298–1 500
Ta_5Si_3	42.95	9.35	−2.13	298–2 000
$TaSi_2$	17.51	1.84	−2.17	298–2 200
V_3Si	22.41	4.37	−1.66	298–1 400
VSi_2	17.08	2.78	−2.25	298–1 950
W_5Si_3	42.94	9.36	−2.13	298–2 200
WSi_2	16.21	2.64	−1.46	298–2 200

Table 8.12e OXIDES
Molar heat capacities

C_p may be given empirically by an equation of the form:

$C_p = 4.186\,8\,(a + 10^{-3}bT + 10^5cT^{-2})$ J K^{-1} mol^{-1}

The values of the constants *a*, *b* and *c* are given below.

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
Ag_2O	14.18	9.75	−1.0		298–500
Al_2O_3	25.48	4.25	−6.82		298–m.p.
As_2O_3	14.30	42.0	—		298–m.p.
B_2O_3 (cryst.)	13.63	17.45	−3.36		298–723
B_2O_3 (glass)	2.28	42.10	—		298–723
B_2O_3 (liq.)	30.45	—	—		900–1 800
BaO	12.74	1.04	−1.984		298–1 270
BeO	9.94	2.44	−4.15	$-32 \times 10^{-6}T^2$	298–2 835
Bi_2O_3 (α)	24.74	8.0	—		298–800
Bi_2O_3 (β)	35.0	—	—		978–1 097
CO	6.79	0.98	−0.11		298–2 500
CO_2	10.55	2.16	−2.04		298–2 500
CaO	11.86	1.08	−1.66		298–1 177
CdO	11.53	1.525	−1.17		298–1 500
CeO_2	15.49	4.23	−1.815		298–1 250
CoO	11.54	2.04	0.4		298–1 800
Co_3O_4	30.84	17.08	−5.72		298–1 000
Cr_2O_3	28.53	2.20	−3.74		350–1 800
Cu_2O	14.90	5.70	—		298–1 200
CuO	9.27	4.80	—		298–1 250
Eu_2O_3(α)	29.60	6.48	−2.08		298–895
Eu_2O_3(β)	31.06	4.16	—		895–1 802
Eu_2O_3 (cubic)	31.90	4.38	−3.04		298–1 350
$Fe_{0.947}O$	11.66	2.00	−0.67		298–m.p.
$Fe_{0.947}O$ (liq.)	16.30	—	—		m.p.–1 800
Fe_3O_4(α)	21.88	48.2	—		298–900
Fe_3O_4(β)	48.00	—	—		900–1 800
Fe_2O_3(α)	23.49	18.6	−3.55		298–950
Fe_2O_3(β)	36.0	—	—		950–1 050
Fe_2O_3(γ)	31.71	1.76	—		1 050–1 750
Gd_2O_3 (monocl.)	27.28	3.54	−2.54		298–1 802
Gd_2O_3 (cubic)	28.72	2.84	−3.88		298–1 550
H_2O (liq.)	18.03	—	—		298–373
H_2O(g)	7.17	2.56	0.08		298–2 500
H_2O_2(g)	12.50	2.84	−2.84		298–1 300
HgO	9.00	6.0	—	estim.	298–?

Table 8.12e OXIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
HfO_2	17.39	2.08	−3.48		298–1 800
IrO_2	17.33	1.93	−3.68		298–1 400
La_2O_3	28.86	3.08	−3.28		298–1 771
Li_2O(s)	14.94	6.08	−3.38		298–1 045
MgO	11.71	0.75	−2.80		298–3 098
MnO	11.11	1.94	−0.88		298–1 800
$Mn_3O_4(\alpha)$	34.64	10.82	−2.20		298–1 445
$Mn_3O_4(\beta)$	50.20	—	—		1 445–1 800
Mn_2O_3(s)	24.73	8.38	−3.23		298–1 350
MnO_2	16.60	2.44	−3.88		298–780
MoO_3	20.07	5.90	−3.68		298–1 068
$Na_2O(\alpha)$	13.26	16.78	0.99	$-7.3\times10^{-6}T^2$	298–1 023
$Na_2O(\beta)$	19.67	3.05	—		1 023–1 243
$Na_2O(\gamma)$	20.28	2.56	—		1 243–m.p.
Na_2O (liq.)	25.0	—	—		m.p. – 2 200
NbO	10.04	2.35	−0.78		298–1 700
$NbO_2(\alpha)$	14.68	6.16	−2.42		298–1 040
$NbO_2(\beta)$	22.20	—	—		1 040–1 200
Nb_2O_5	38.76	3.54	−7.32		298–1 780
$Nd_2O_3(\alpha)$	27.67	7.12	−2.84		298–1 395
$Nd_2O_3(\beta)$	37.20	—	—		1 395–1 795
$NiO(\alpha)$	−4.99	37.58	3.89		298–525
$NiO(\beta)$	13.88	—	—		525–565
$NiO(\gamma)$	11.18	2.02	—		565–1 800
P_2O_5	17.90	38.8	−3.73		298–700
P_4O_{10}(g)	73.6	—	—		631–1 400
PbO (red)	10.95	3.75	−1.0		298–1 900
PbO (yell.)	9.05	6.40	—		298–1 000
PbO_2	12.7	7.8	—	estim.	298–?
PdO	10.83	1.68	−0.80	$+0.09\times10^{-6}T^2$	298–1 200
Pr_6O_{11}	95.29	26.16	−9.31		298–1 172
Rh_2O	15.59	6.47	—		298–973
RhO	9.84	5.33	—		298–1 023
Rh_2O_3	20.74	13.8	—		298–973
SO(g)	7.70	0.84	−0.65		298–2 000
SO_2(g)	10.38	2.54	−1.42		298–1 800
SO_3(g)	13.70	6.42	−3.12		298–1 200
Sb_2O_3	19.10	17.1	—	estim.	298–930
SbO_2	11.30	8.1	—	estim.	298–1 198
Sb_2O_5	10.95	57.57	—		298–500
Sc_2O_3	23.17	5.64	—	estim.	298–2 500
α-quartz	10.49	0.24	−1.44		298–848
β-quartz	14.08	2.4	—		848–2 000
α-cristobalite	4.28	21.06	—		298–523
β-cristobalite	17.39	0.31	−9.90		523–2 000
α-tridymite	3.27	24.80	—		298–390
β-tridymite	13.64	2.64	—		390–2 000
SiO_2 (glass)	13.38	3.68	−3.45		298–2 000
$Sm_2O_3(\alpha)$	30.75	4.64	−4.30		298–1 195
$Sm_2O_3(\beta)$	36.90	—	—		1 195–1 798
Sm_2O_3 (cubic)	30.64	5.08	−3.96		298–1 150
SnO_2	17.66	2.40	−5.16		298–1 500
SrO	12.34	1.12	−1.806		298–1 270
Ta_2O_5	37.0	6.56	−5.92		298–1 800
TeO_2	15.58	3.48	−1.20		298–m.p.

Table 8.12e OXIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
TeO_2 (liq.)	26.95	0.52	—		m.p.–1 146
ThO_2	16.65	2.13	−2.24		298–2 500
$TiO(\alpha)$	10.57	3.6	−1.86		298–1 264
$TiO(\beta)$	11.85	3.0	—		1 264–1 800
$Ti_2O_3(\alpha)$	7.31	53.52	—		298–473
$Ti_2O_3(\beta)$	34.68	1.3	−10.2		473–1 800
$Ti_3O_5(\alpha)$	35.47	29.50	—		298–450
$Ti_3O_5(\beta)$	41.60	8.0	—		450–1 400
rutile	17.97	0.28	−4.35		298–1 800
anatase	17.83	0.50	−4.23		298–1 300
UO_2	19.20	1.62	−3.96		298–1 500
U_3O_8	67.5	8.83	−11.94		298–900
UO_3	22.1	2.64	−2.65		298–900
VO	11.32	3.22	−1.26		298–1 700
V_2O_3	29.35	4.76	−5.42		298–1 800
$VO_2(\alpha)$	14.96	—	—		298–345
$VO_2(\beta)$	17.85	1.70	−3.95		345–1 818
VO_2 (liq.)	25.5	—	—		1 818–1 900
V_2O_5	46.54	−3.90	−13.22		298–943
V_2O_5 (liq.)	45.60	—	—		943–1 500
WO_3	17.48	6.79	—	estim.	298–1 550
$Y_2O_3(\alpha)$	29.60	1.20	−4.78		298–1 330
$Y_2O_3(\beta)$	31.50	—	—		1 330–1 800
ZnO	11.71	1.22	−2.18		298–1 600
$ZrO_2(\alpha)$	16.64	1.80	−3.36		298–1 478
$ZrO_2(\beta)$	17.80	—	—		1 478–1 850

Table 8.12f SULPHIDES, SELENIDES AND TELLURIDES

Molar heat capacities

C_p may be given empirically by an equation of the form:

$C_p = 4.1868\,(a + 10^{-3}bT + 10^5 cT^{-2})\ \mathrm{J\,K^{-1}\,mol^{-1}}$

The values of the constants are given below.

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
$Ag_2S(\alpha)$	10.13	26.40	—		298–452
$Ag_2S(\beta)$	21.64	—	—		452–850
$Ag_2Se(\alpha)$	23.29	0.39	−4.0		298–406
$Ag_2Se(\beta)$	20.4	—	—		406–460
Bi_2S_3	26.25	9.8	—	estim.	—
Bi_2Te_3	36.0	13.05	−3.12		373–m.p.
CS_2(l)	18.4	—	—		298–b.p.
CS_2(g)	12.45	1.60	−1.80		298–1 800
CaS	10.80	1.85	—	estim.	298–2 000
CdS	10.65	3.30	—	estim.	273–1 273
CdTe	12.55	4.54	−1.76		298–m.p.
CoS	10.6	2.51	—	estim.	273–1 373
$Cu_2S(\alpha)$	19.50	—	—		298–376
$Cu_2S(\beta)$	23.25	—	—		376–623
$Cu_2S(\gamma)$	20.32	—	—		623–1 400
CuS	10.6	2.64	—	estim.	273–1 273
$Cu_2Se(\alpha)$	14.0	18.5	—		298–395
$Cu_2Se(\beta)$	20.1	—	—		383–488
$Cu_2Te(\zeta)$	20.9	—	—		841–950
$Cu_2Te(\epsilon)$	26.12	—	—		633–841

Table 8.12f SULPHIDES, SELENIDES AND TELLURIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
$Cu_2Te(\delta)$	32.0	—	—		590–633
$Cu_2Te(\gamma)$	27.0	—	—		531–590
$Cu_2Te(\beta)$	14.45	12.8	—		433–531
$Cu_2Te(\alpha)$	14.3	12.8	—		298–433
$FeS(\alpha)$	5.19	26.40	—		298–411
$FeS(\beta)$	17.40	—	—		411–598
$FeS(\gamma)$	12.20	2.38	—		598–1 468
FeS(l)	17.0	—	—		1 468–1 500
FeS_2	17.88	1.32	−3.05		298–1 000
$H_2S(g)$	7.81	2.96	−0.46		298–2 000
$H_2Se(g)$	7.59	3.50	−0.31		298–2 000
MnS	11.40	1.80	—		298–1 803
MnS(liq.)	16.00	—	—		1 803–2 000
$MoS_2(s)$	11.2	13.5	—	estim.	298–729
NiS	9.3	6.4	—		273–670
NiTe(s)	11.57	3.30	—		298–700
PbS	10.63	4.01	—		273–873
PtS	11.95	2.6	−2.12	estim.	298–1 100
PtS_2	14.07	7.08	−0.4	estim.	298–1 000
Sb_2S_3	24.2	13.2	—	estim.	273–821
$SnS(\alpha)$	8.53	7.48	0.9		298–875
$SnS(\beta)$	9.78	3.74	—		875–m.p.
SnS(l)	17.90	—	—		1 153–1 250
SnS_2	15.51	4.20	—		298–1 000
SnTe	16.88	3.67	—		273–603
$TiS_2(\alpha)$	8.08	27.34	—		298–420
$TiS_2(\beta)$	14.99	5.14	—		420–1 010
ZnS(s)	12.16	1.24	−1.36		298–1 200
ZnTe	11.11	2.61	—	—	298–m.p.

Table 8.12g HALIDES

Molar heat capacities

C_p may be given empirically by an equation of the form:

$C_p = 4.1868\ (a + 10^{-3}bT + 10^{5}cT^{-2})$ J K^{-1} mol^{-1}

The values of the constants are given in the following table.

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
AgCl(s)	14.88	1.0	−2.70		298–728
AgCl(l)	16.0	—	—		728–900
AgBr(s)	7.93	15.40	—		298–703
AgBr(l)	14.9	—	—		m.p.–836
$AgI(\alpha)$	5.82	24.10	—		298–423
$AgI(\beta)$	13.5	—	—		423–600
$AlCl_3(s)$	13.25	28.00	—		273–m.p.
$AlCl_3(l)$	31.2	—	—		m.p.–504
AlCl(g)	9.0	—	−0.68		298–2 000
$AlBr_3(s)$	18.74	18.66	—		273–m.p.
$AlBr_3(l)$	29.5	—	—		m.p.–407
$AlI_3(s)$	16.88	22.66	—		273–m.p.
$AlI_3(l)$	28.8	—	—		m.p.–480
$AlF_3(\alpha)$	17.27	10.96	−2.30		298–727
$AlF_3(\beta)$	20.93	3.0	—		727–1 400

Table 8.12g HALIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
AlF(g)	8.9	—	−1.45		298–2 000
$AsCl_3$(l)	31.9	—	—	estim.	286–371
$AsCl_3$(g)	19.62	0.24	−1.42		298–1 000
AsF_3(l)	30.2	—	—		298
AsF_3(g)	18.18	1.66	−2.66		298–1 000
$BaCl_2$(α)	22.20	0.76	−4.0		273–1 198
$BaCl_2$(β)	26.61	—	—		1 198–m.p.
$BaCl_2$(l)	24.96	—	—		m.p.–1 339
$BaBr_2$(s)	15.96	6.22	—		487–1 126
CCl_4(g)	24.90	0.48	−4.74		298–1 000
CBr_4(α)	31.7	—	—		295–320
CBr_4(β)	33.0	—	—		320–m.p.
CBr_4(g)	25.03	0.60	−3.03		298–1 000
CF_4(g)	16.64	7.84	−4.00		298–1 200
$CaCl_2$(s)	17.18	3.04	−0.6		600–1 055
$CaCl_2$(l)	24.70	—	—		1 055–1 700
$CaBr_2$(s)	13.96	7.86	—		434–m.p.
$CaBr_2$(l)	27.38	—	—		m.p.–1 132
CaF_2(α)	14.30	7.28	0.47		298–1 424
CaF_2(β)	25.81	2.5	—		1 424–m.p.
CaF_2(l)	23.88	—	—		m.p.–1 800
$CoCl_2$(s)	14.41	14.60	—		298–1 000
$CrCl_2$(s)	15.23	5.96	—		298–m.p.
$CrCl_3$(s)	19.44	7.03	—		298–m.p.
CsBr(s)	11.6	2.59	—	estim.	273–909
CsCl(α)	12.78	1.23	−0.46		293–743
CsCl(β)	0.81	17.64	−0.89		743–m.p.
CsCl(l)	13.86	4.28	—		m.p.–1 170
CsF(s)	11.3	2.71	—	estim.	273–957
CsI(s)	7.06	10.36	1.93		298–m.p.
CsI(l)	−4.29	20.5	—		m.p.–1 170
CuCl(s)	5.87	19.2	—		298–703
CuCl(l)	15.8	—	—		703–1 200
CuCl(g)	8.92	—	−0.47		298–2 000
$CuCl_2$(s)	15.42	12.0	—		298–800
CuI(s)	12.1	2.86	—	estim.	273–675
CuI_2(s)	20.1	—	—	estim.	274–328
$FeCl_2$(s)	18.94	2.08	−1.17		600–950
$FeCl_2$(l)	24.42	—	—		950–1 100
$FeCl_3$(s)	29.56	—	−6.11		298- m.p.
HF(g)	6.43	0.82	0.26		298–2 000
HCl(g)	6.34	1.10	0.26		298–2 000
HBr(g)	6.25	1.40	0.26		298–1 600
HI(g)	6.29	1.42	0.22		298–2 000
HfF_4(s)	31.9	74.8	9.0		273–1 103
$HfCl_4$(s)	31.47	—	−2.38		298–485
HgCl(s)	11.05	3.70	—	estim.	273–798
$HgCl_2$(s)	15.3	10.3	—	estim.	273–553
HgI(s)	11.4	4.61	—	estim.	273–563
HgI_2(α)	18.50	—	—		298–403
HgI_2(β)	20.2	—	—		403–m.p.
HgI_2(l)	25.0	—	—		m.p.–603
KCl(s)	9.89	5.20	0.77		298–1 043
KCl(l)	16.0	—	—		1 043–1 200
KCl(g)	8.94	0.18	−0.24		298–2 000

Table 8.12g HALIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
KBr(s)	12.84	2.50	−2.84		600–1 000
KBr(g)	8.94	—	−0.17		298–2 000
KI(s)	21.10	−8.38	−10.38		600–1 000
KF(s)	11.02	3.12	—		298–1 130
LiCl(s)	11.0	3.39	—	estim.	273–887
LiBr(s)	11.5	3.02	—	estim.	273–825
LiF(s)	9.14	5.19	—		298–m.p.
LiF(l)	15.50	—	—		m.p.–1 170
LiI(s)	12.5	2.08	—	estim.	273–723
$MgCl_2$(s)	18.90	1.42	−2.06		600–987
$MgCl_2$(l)	22.10	—	—		987–1 500
MgF_2(s)	16.93	2.52	−2.20		298–m.p.
MgF_2(l)	22.57	—	—		1 538–1 800
$MnCl_2$(s)	18.04	3.16	−1.37		600–923
$MnCl_2$(l)	22.60	—	—		923–1 200
MnF_2(s)	14.79	5.70	−0.47		298–m.p.
NaCl(s)	10.98	3.90	—		298–1 073
NaCl(l)	16.0	—	—		m.p.–1 300
NaCl(g)	8.93	—	−0.41		298–2 000
NaBr(s)	11.87	2.10	—		298–550
NaBr(g)	8.93	—	−0.29		298–2 000
NaF(s)	10.40	3.88	−0.33		298–m.p.
NaI(s)	12.5	1.62	—	estim.	273–936
$NH_4Cl(\alpha)$	11.80	32.0	—		298–457.7
$NH_4Cl(\beta)$	5.00	34.0	—		457.7–500
$NiCl_2$(s)	17.50	3.16	−1.19		298–1 303
$NiCl_2$(l)	24.00	—	—		1 303–1 336
PF_3(g)	17.18	1.92	−3.88		298–2 000
PCl_3(l)	28.7	—	—	estim.	284–371
PCl_3(g)	19.15	0.74	−1.91		298–1 000
PCl_5(g)	31.42	0.20	−4.27		298–2 000
PBr_3(g)	19.81	—	−1.43		298–1 000
$PbCl_2$(s)	16.1	4.0	—		298–771
$PbCl_2$(l)	28.2	—	—		m.p.–851
$PbBr_2$(s)	18.59	2.20	—		298–643
$PbBr_2$(l)	27.6	—	—		m.p.–860
PbI_2(s)	18.00	4.70	—		298–685
PbI_2(l)	32.3	—	—		m.p.–776
PbF_2(s)	16.5	4.12	—	estim.	273–1 091
RbF(s)	7.97	9.2	1.21		298–m.p.
RbF(l)	−11.30	0.88	350.7		m.p.–1 200
RbCl(s)	11.5	2.49	—	estim.	273–987
RbBr(s)	11.6	2.55	—	estim.	273–954
RbI(s)	11.6	2.63	—	estim.	273–913
$SbCl_3$(s)	10.3	51.1	—	estim.	273–346
$SbBr_3$(s)	17.2	29.3	—	estim.	273–370
$SiCl_4$(g)	24.25	1.64	−2.75		298–1 000
$SiBr_4$(g)	25.19	0.64	−1.94		298–1 000
SiF_4(g)	21.86	3.15	−4.70		298–1 000
$SnCl_2$(s)	16.2	9.26	—	estim.	273–520
$SnCl_4$(l)	39.5	—	—	estim.	286–371
$SnCl_4$(g)	25.57	0.20	−1.87		298–1 000
$SnBr_4$(g)	25.80	—	−0.97		298–1 000
SnI_4(s)	19.4	36.0	—		298–b.p.
SnI_4(l)	40.1	—	—		b.p.–443

Table 8.12g HALIDES—*continued*

Compound	*a*	*b*	*c*	*Remarks*	*Temp. range* K
$TeCl_4$(s)	33.1	—	—		298–m.p.
$TeCl_4$(l)	53.2	—	—		m.p.–538
TeF_6(g)	35.33	1.62	−7.00		298–2 000
$TiCl_4$(l)	35.7	—	—	estim.	273–372
$TiCl_4$(g)	25.45	0.24	−2.36		298–2 000
$TiBr_4$(s)	28.0	—	—		298–m.p.
$TiBr_4$(l)	32.75	15.66	—		m.p.–423
TlCl(s)	12.00	2.00	—		298–700
TlCl(l)	14.2	—	—		m.p.–803
TlCl(g)	8.94	—	−0.25		298–2 000
TlBr(s)	11.07	4.95	—		298–733
TlBr(l)	25.25	−9.04	—		m.p.–800
UF_4(s)	25.7	7.00	−0.06		298–1 309
UF_6(s)	12.6	92.0	—		273–337
UF_6(g)	22.3	28.5	—		273–400
UCl_3(s)	20.8	7.75	1.05		298–900
UCl_4(s)	27.2	8.57	−0.79		298–800
UCl_4(l)	25.8	14.4	—		890–920
UBr_4(s)	31.4	4.92	−3.15		350–750
UI_4(s)	34.8	2.38	−4.72		380–720
UI_4(l)	39.6	—	—		820–870
VCl_2(s)	17.25	2.72	−0.71		298–1 200
VCl_3(s)	22.99	3.92	−1.68		298–900
$ZnCl_2$(s)	14.5	5.5	—		298–m.p.
$ZnCl_2$(l)	24.1	—	—		m.p.–1 000
$ZnBr_2$(s)	12.6	10.4	—		298–m.p.
$ZnBr_2$(l)	27.2	—	—		m.p.–1 000
$ZrCl_4$(s)	31.92	—	−2.91		298–604
$ZrBr_4$(s)	25.5	15.1	—	estim.	298–630

8.7 Vapour pressures

Table 8.13 ELEMENTS
Vapour pressures

The vapour pressure p (mmHg) of an element may be represented by an equation of the type:

$$\log p = -\frac{A}{T} + B + C \log T + 10^{-3}DT$$

The values of the constants A, B, C and D in this equation are given below.

Element	*A*	*B*	*C*	*D*	*Temp. range* K
Ag	14 710	11.66	−0.755	—	298–1 234
	14 260	12.23	−1.055	—	1 234–2 400
Al	16 450	12.36	−1.023	—	1 200–2 800
Am	13 700	13.97	−1.0	—	1 103–1 453
As_4	6 160	9.82	—	—	600–900
Au	19 820	10.81	−0.306	−0.16	298–1 336
	19 280	12.38	−1.01	—	1 336–3 240
B	29 900	13.88	−1.0	—	1 000–m.p.
Ba	9 730	7.83	—	—	750–983
	9 340	7.42	—	—	983–1 200
Be	10 734	9.067	—	−0.145	900–1 557
Bi	10 400	12.35	−1.26	—	m.p.–b.p.
Bi_2	10 730	18.1	−3.02	—	m.p.–b.p.

Table 8.13 ELEMENTS—*continued*

Element	*A*	*B*	*C*	*D*	*Temp. range* K
Ca	10 300	14.97	−1.76	—	713–m.p.
	9 600	12.55	−1.21	—	m.p.–b.p.
Ce	20 305	8.305	—	—	1 611–2 038
Cd	5 908	9.717	−0.232	−0.284	450–594
	5 819	12.287	−1.257	—	594–1 050
Co	22 210	10.817	—	−0.223	1 000–1 772
Cr	20 680	14.56	−1.31	—	298–m.p.
Cs	4 075	11.38	−1.45	—	280–1 000
Cu	17 870	10.63	−0.236	−0.16	298–1 356
	17 650	13.39	−1.273	—	1 356–2 870
Eu	8 980	8.16	—	—	696–900
Fe	21 080	16.89	−2.14	—	900–1 812
	19 710	13.27	−1.27	—	1 812–3 000
Ga	14 700	10.07	−0.5	—	m.p.–b.p.
Ge	20 150	13.28	−0.91	—	298–m.p.
	18 700	12.87	−1.16	—	m.p.–b.p.
Hf(α)	32 000	11.81	−0.5	—	298–2 023
Hf(β)	31 630	11.63	−0.5	—	2 023–m.p.
Hf	29 830	9.20	—	—	m.p.–b.p.
Hg	3 308	10.373	−0.8	—	298–630
I_2	3 578	17.72	−2.51	—	298–m.p.
	3 205	23.65	−5.18	—	m.p.–b.p.
In	12 580	9.79	−0.45	—	m.p.–b.p.
Ir	35 070	13.18	−0.7	—	298–m.p.
K	4 770	11.58	−1.370	—	350–1 050
La	22 120	10.39	−0.33	—	298–m.p.
	21 530	9.89	−0.33	—	m.p.–b.p.
Li	8 415	11.34	−1.0	—	m.p.–b.p.
Mg	7 780	11.41	−0.855	—	298–m.p.
	7 550	12.79	−1.41	—	m.p.–b.p.
Mn	14 850	17.88	−2.52	—	993–1 373
	13 900	17.27	−2.52	—	m.p.–b.p.
Mo	34 700	11.66	−0.236	−0.145	298–m.p.
Na	5 700	11.33	−1.718	—	400–1 200
Na_2	6 540	10.7	—	—	—
Nb	37 650	8.94	+0.715	−0.166	298–m.p.
Ni	22 500	13.60	−0.96	—	298–m.p.
	22 400	16.95	−2.01	—	m.p.–b.p.
P_4 (yell.)	3 530	19.09	−3.5	—	298–317
P_4	2 740	7.84	—	—	317–553
Pb	10 130	11.16	−0.985	—	600–2 030
Pd	19 800	11.82	−0.755	—	298–m.p.
	17 500	4.81	+1.0	—	m.p.–b.p.
Pr	17 190	8.10	—	—	1 425–1 692
Pt	29 200	13.24	−0.855	—	298–m.p.
	28 500	14.30	−1.26	—	m.p.–b.p.
Pu	17 590	7.90	—	—	1 392–1 793
Rb	4 560	12.00	−1.45	—	312–952
Re	40 800	14.20	−1.16	—	298–3 000
Rh	29 360	13.50	−0.88	—	298–m.p.
Ru	33 550	10.76	—	—	2 000–2 500
S_2	6 975	16.22	−1.53	−1.0	m.p.–b.p.
S_x	4 830	23.88	−5.0	—	m.p.–b.p.
Sb_x	11 560	22.40	−3.52	—	298–m.p.
Sb_2	11 170	18.54	−3.02	—	m.p.–b.p.
Sc(β)	19 700	13.07	−1.0	—	1 607–m.p.
Se_x	4 990	8.09	—	—	493–958

Table 8.13 ELEMENTS - *continued*

Element	*A*	*B*	*C*	*D*	*Temp. range* K
Si	20 900	10.84	−0.565	—	m.p.–b.p.
Sm	11 170	13.76	−1.56	~	298–m.p.
Sn	15 500	8.23	—	—	505–b.p.
Sr	9 450	13.08	−1.31	—	813–m.p.
	9 000	12.63	−1.31	—	m.p.–b.p.
Tu	40 800	10.29	—	—	298–m.p.
Te_2	9 175	19.68	−2.71	—	298–m.p.
	7 830	22.29	−4.27	—	m.p.–
Th	30 200	12.95	−1.0	—	298–m.p.
Ti(β)	24 400	13.18	−0.91	—	1 155–m.p.
Ti	23 200	11.74	−0.66	—	m.p.–b.p.
Tl	9 300	11.10	−0.892	—	700–1 800
Tm	12 550	9.18	—	—	807–1 219
U	25 580	18.58	−2.62	—	298–1 405
	24 090	13.20	−1.26	—	1 405–4 200
V	26 900	10.12	+0.33	−0.265	298–m.p.
W	44 000	8.76	+0.50	—	298–m.p.
Y	22 230	11.835	−0.66	—	298–m.p.
	22 280	16.13	−1.97	—	m.p.–b.p.
Zn	6 883	9.418	−0.050 3	−0.33	473–692.5
	6 670	12.00	−1.126	—	692.5–1 000
Zr	31 820	11.78	−0.50	—	1 125–m.p.
	30 300	9.38	—	—	m.p.–b.p.

Table 8.14 HALIDES AND OXIDES

Vapour pressures

$$\log p = \frac{A}{T} + B + C \log T + 10^{-3} D T \text{ (mmHg)}$$

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
AgCl	−11 830	12.39	−0.30	−1.02	298–m.p.
AgCl	−11 320	17.34	−2.55	—	m.p.–b.p.
AgBr	−12 400	19.33	−2.97	—	m.p.–b.p.
AgI	−10 250	20.09	−3.52	—	m.p.–b.p.
AlF_3	−16 700	23.27	−3.02	—	298–s.p.
Al_2Cl_6	−6 360	9.66	3.77	−6.12	298–s.p.
Al_2Br_6	−5 280	20.81	−1.75	−4.08	298–m.p.
Al_2Br_6	−5 280	46.70	−12.59	—	m.p.–b.p.
Al_2I_6	−7 150	17.76	0.12	−4.96	298–m.p.
Al_2I_6	−6 760	46.67	−11.89	—	m.p.–b.p.
AmF_3	−24 600	36.87	−7.05	—	1 100–1 300
AsF_3	−4 150	61.38	−18.26	—	265–292
AsF_5	−1 088	7.72	—	—	m.p.–b.p.
$AsCl_3$	−2 660	24.76	−5.83	—	m.p.–b.p.
As_4O_6*	−5 282	10.91	—	—	373–573
As_4O_6†	−5 452	11.468	—	—	488–573
As_4O_6	−3 130	7.16	—	—	m.p.–b.p.
BCl_3	−2 115	27.56	−7.04	—	m.p.–b.p.
BBr_3	−2 710	28.36	−7.04	—	m.p.–b.p.
BI_3	−3 342	24.31	−5.4	—	m.p.–b.p.

* claudetite † arsenolite

Table 8.14 HALIDES AND OXIDES—*continued*

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
B_2O_3	−16 960	6.64	—	—	1 300–1 650
BaF_2	−20 330	28.04	−5.03	—	m.p.–b.p.
BaO	−21 900	9.99	—	—	1 200–1 700
BeF_2	−13 000	24.56	−3.79	—	m.p.–b.p.
Be_2Cl_4	−8 970	37.0	−7.65	—	298–m.p.
$BeCl_2$	−7 870	27.15	−5.03	—	298–m.p.
$BeCl_2$	−7 220	26.28	−5.03	—	m.p.–b.p.
Be_2Br_4	−8 320	35.9	−7.65	—	298–s.p.
$BeBr_2$	−7 650	27.15	−5.03	—	298–m.p.
$BeBr_2$	−6 570	25.63	−5.03	—	m.p.–b.p.
Be_2I_4	−8 520	35.9	−7.65	—	298–m.p.
BeI_2	−7 000	26.5	−5.03	—	298–m.p.
BeI_2	−5 800	24.96	−5.03	—	m.p.–b.p.
$BiCl_3$	−6 200	12.83	—	—	298–m.p.
$BiCl_3$	−5 980	31.38	−7.04	—	m.p.–b.p.
$BiBr_3$	−6 190	31.40	−7.04	—	m.p.–b.p.
CCl_4	−2 400	23.60	−5.30	—	m.p.–b.p.
CBr_4	−2 650	8.78	—	—	298–m.p.
CBr_4	−2 330	7.89	—	—	m.p.–b.p.
$CaF_2(\alpha)$	−23 600	27.41	−4.525	—	298–1 424
$CaF_2(\beta)$	−23 350	27.23	−4.525	—	1 424–m.p.
CaF_2	−21 800	26.31	−4.525	—	m.p.–b.p.
$CaCl_2$	−13 570	9.22	—	—	1 110–1 281
CdF_2	−16 170	27.50	−5.03	—	m.p.–b.p.
$CdCl_2$	−9 270	17.46	−2.11	—	298–m.p.
$CdCl_2$	−9 183	25.907	−5.04	—	m.p.–b.p.
$CdBr_2$	−8 250	18.15	−2.5	—	298–m.p.
$CdBr_2$	−7 150	16.85	−2.5	—	m.p.–b.p.
CdI_2	−7 530	18.01	−2.5	—	298–m.p.
CdI_2	−6 720	16.79	−2.5	—	m.p.–b.p.
$CeCl_3$	−18 750	36.38	−7.05	—	298–m.p.
$CeBr_3$	−18 000	36.49	−7.05	—	298–m.p.
$CoCl_2$	−14 150	30.10	−5.03	—	298–m.p.
$CoCl_2$	−11 050	27.06	−5.03	—	m.p.–b.p.
$CrCl_2$	−14 000	15.14	−0.62	−0.58	298–m.p.
$CrCl_2$	−13 800	27.70	−5.03	—	m.p.–b.p.
$CrCl_3$	−13 950	17.49	−0.73	−0.77	298–s.p.
CrI_2	−16 080	25.92	−3.53	—	298–m.p.
CrO_2Cl_2	−3 340	34.94	−9.08	—	m.p.–b.p.
CsF	−10 930	17.51	−2.12	—	298–m.p.
CsF	−9 950	18.62	−2.84	—	m.p.–b.p.
CsCl	−10 800	19.99	−3.02	—	700–m.p.
CsCl	−9 815	20.38	−3.52	—	m.p.–b.p.
CsBr	−10 950	20.02	−3.02	—	700–m.p.
CsBr	−10 080	20.56	−3.52	—	m.p.–b.p.
CsI	−10 420	19.70	−3.02	—	600–m.p.
CsI	−9 678	20.35	−3.52	—	m.p.–b.p.
CuCl	−10 170	8.04	—	—	1 000–1 900
Cu_3Cl_3	−3 750	4.90	—	—	900–1 800
CuBr	−7 700	7.69	—	—	1 000–1 480
Cu_3Br_3	−4 010	4.88	—	—	1 000–2 000
$Cu_3I_3(\alpha)$	−9 463	11.14	—	—	629
$Cu_3I_3(\beta)$	−8 351	9.41	—	—	643–670
$Cu_3I_3(\gamma)$	−7 853	8.68	—	—	684–770
$FeCl_2$	−9 890	11.10	—	—	670–740

Table 8.14 HALIDES AND OXIDES—*continued*

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
$FeBr_2$	−10 220	11.95	—	—	670–740
FeI_2	−12 180	29.59	−5.03	—	298–m.p.
FeI_2	−8 750	27.185	−5.535	—	m.p.–b.p.
Fe_2Cl_6	−9 540	45.53	−9.5	—	298–m.p.
$Fe(CO)_5$	−2 075	8.42	—	—	298–b.p.
$GaCl_2$	−4 886	29.14	−6.44	—	m.p.–b.p.
$GaBr_3$	−4 700	28.69	−6.44	—	m.p.–b.p.
$GeCl_4$	−2 940	34.27	−9.08	—	m.p.–b.p.
$GeBr_4$	−3 690	35.00	−9.05	—	m.p.–b.p.
GeI_4	−4 920	22.73	−4.02	—	298–m.p.
H_2O	−2 900	22.613	−4.65	—	m.p.–b.p.
H_2O_2	−3 560	29.68	−7.04	—	m.p.–
$HfCl_4$	−5 200	11.71	—	—	476–681
$HfI_4(\alpha)$	−10 700	19.56	—	—	575–597
$HfI_4(\beta)$	−7 360	13.97	—	—	598–645
$HfI_4(\gamma)$	−6 173	12.13	—	—	648–678
$HgCl_2$	−4 580	16.39	−2.0	—	298–m.p.
$HgBr_2$	−4 500	11.47	0.05	−1.51	298–m.p.
$HgBr_2$	−4 370	24.18	−5.03	—	m.p.–b.p.
HgI_2	−5 690	30.27	−6.47	—	298–m.p.
HgI_2	−4 620	25.72	−5.33	—	m.p.–b.p.
InCl	−4 640	8.03	—	—	m.p.–b.p.
$InCl_3$	−8 270	13.62	—	—	500–s.p.
InBr	−6 470	16.31	−2.01	—	298–m.p.
$InBr_2$	−4 480	7.48	—	—	m.p.–b.p.
$InBr_3$	−5 670	11.67	—	—	500–s.p.
InI	−6 730	15.74	−1.97	—	298–m.p.
IrF_6	−1 657	7.952	—	—	m.p.–b.p.
KF	−12 930	17.30	−2.06	—	298–m.p.
KF	−11 570	16.90	−2.32	—	m.p.–b.p.
KCl	−12 230	20.34	−3.0	—	298—m.p.
KCl	−10 710	18.91	−3.0	—	m.p.–b.p.
KBr	−11 110	16.60	−2.0	—	298–m.p.
KBr	−10 180	18.67	−3.0	—	m.p.–b.p.
KI	−11 000	16.99	−2.0	—	298–m.p.
KI	−10 050	20.41	−3.52	—	m.p.–b.p.
$LaCl_3$	−19 040	36.20	−7.05	—	298–m.p.
$LaBr_3$	−18 780	36.83	−7.05	—	298–m.p.
LaI_3	−18 390	37.00	−7.05	—	298–m.p.
LiF	−14 560	23.56	−4.02	—	m.p.–b.p.
LiCl	−10 760	22.30	−4.02	—	m.p.–b.p.
LiBr	−10 170	20.55	−3.52	—	m.p.–b.p.
LiI	−11 110	21.70	−3.52	—	m.p.–b.p.
MgF_2	−19 700	27.80	−5.03	—	m.p.–b.p.
$MgCl_2$	−10 840	25.53	−5.03	—	m.p.–b.p.
$MgBr_2$	−10 930	26.07	−5.03	—	m.p.–b.p.
MgI_2	−8 090	25.18	−5.03	—	m.p.–b.p.
MnF_2	−17 400	22.06	−3.02	—	m.p.–b.p.
$MnCl_2$	−10 606	23.68	−4.33	—	m.p.–b.p.
MoF_5	−2 772	8.58	—	—	m.p.–b.p.
MoF_6	−1 500	7.77	—	—	m.p.–b.p.
$MoOF_4$	−2 854	9.21	—	—	313–m.p.
$MoOF_4$	−2 671	8.716	—	—	m.p.–b.p.
$MoCl_5$	−5 210	13.1	—	—	298–m.p.
MoO_3	−15 230	27.16	−4.02	—	298–m.p.

Table 8.14 HALIDES AND OXIDES – *continued*

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
MoO_3	−12 480	24.60	−4.02	—	m.p.–b.p.
NaF	−14 960	17.53	−2.01	—	298–m.p.
NaF	−13 500	17.93	−2.52	—	m.p.–b.p.
NaCl	−12 440	14.31	−0.90	−0.46	298–m.p.
NaCl	−11 530	20.77	−3.48	—	m.p.–b.p.
NaBr	−12 100	20.39	−3.0	—	298–m.p.
NaBr	−10 500	18.81	−3.0	—	m.p.–b.p.
NaI	−10 740	20.96	−3.52	—	m.p.–b.p.
NbF_5	−4 900	14.397	—	—	298–m.p.
NbF_5	−2 780	8.37	—	—	m.p.–b.p.
$NbCl_4$	−6 870	12.30	—	—	577–651
$NbCl_5$	−4 370	11.51	—	—	403–m.p.
$NbCl_5$	−2 870	8.37	—	—	m.p.–b.p.
$NbBr_5$	−4 085	9.33	—	—	m.p.–b.p.
$NbOCl_3$	−5 333	8.79	—	—	298–s.p.
$NdCl_3$	−18 220	36.27	−7.05	—	298–m.p.
$NdBr_3$	−17 650	36.51	−7.05	—	298–m.p.
NdI_3	−17 490	36.61	−7.05	—	298–m.p.
NiF_2	−14 650	20.28	−3.02	—	298–m.p.
$NiCl_2$	−13 300	21.88	−2.68	—	298–s.p.
$NiBr_2$	−13 110	16.68	−1.71	−0.35	298–s.p.
$Ni(CO)_4$	−1 530	7.73	—	—	298–b.p.
NpF_6	−2 892	18.48	−2.7	—	273–m.p.
	−1 913	14.61	−2.35	—	m.p.–350
OsF_5	−3 429	9.75	—	—	m.p.–b.p.
OsF_6	−1 858	8.726	—	—	273–m.p.
OsF_6	−1 473	7.47	—	—	m.p.–b.p.
OsO_4*	−2 955	9.64	—	—	273–329
OsO_4†	−2 580	10.70	—	—	273–315
OsO_4	−2 065	8.01	—	—	m.p.–b.p.
PCl_3	−2 370	22.74	−5.14	—	273–b.p.
PCl_5	−3 520	11.035	—	—	373–432
$POCl_3$	−1 830	7.72	—	—	273–b.p.
P_4O_{10}‡	−4 350	9.81	—	—	298–s.p.
PbF_2	−11 800	26.48	−5.03	—	m.p.–b.p.
$PbCl_2$	−9 890	15.36	−0.95	−0.91	298–m.p.
$PbCl_2$	−10 000	31.60	−6.65	—	m.p.–b.p.
$PbBr_2$	−9 320	18.44	−2.08	−0.34	298–m.p.
$PbBr_2$	−9 540	31.67	−6.76	—	m.p.–b.p.
PbI_2	−9 340	19.68	−2.35	−0.32	298–m.p.
PbI_2	−10 000	39.80	−9.21	—	m.p.–b.p.
PbO	−13 480	14.36	−0.92	−0.35	298–m.p.
PbO	−13 310	19.47	−2.77	—	m.p.–b.p.
$PrCl_3$	−18 490	36.31	−7.05	—	298–m.p.
$PrBr_3$	−17 800	36.53	−7.05	—	298–m.p.
PrI_3	−17 470	36.66	−7.05	—	298–m.p.
PuF_3	−24 950	36.91	−7.05	—	298–m.p.
PuF_3	−23 500	34.47	−6.45	—	m.p.–200
$PuCl_3$	−18 270	32.60	−5.34	—	298–m.p.
$PuCl_3$	−15 490	31.76	−6.45	—	m.p.–b.p.
$PuBr_3$	−17 460	31.32	−5.34	—	298–m.p.
$PuBr_3$	−15 030	32.34	−6.45	—	m.p.–b.p.
RbF	−11 230	18.26	−2.66	—	m.p.–b.p.
RbCl	−11 670	20.157	−3.0	—	298–m.p.

* yellow † white ‡ hexagonal

Table 8.14 HALIDES AND OXIDES—*continued*

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
RbCl	−10 300	18.77	−3.0	—	m.p.–b.p.
RbBr	−11 510	20.155	−3.0	—	298–m.p.
RbBr	−10 220	18.805	−3.0	—	m.p.–b.p.
RbI	−10 280	20.64	−3.52	—	m.p.–b.p.
ReF_5	−3 037	9.024	—	—	m.p.–b.p.
ReF_6	−1 489	7.732	—	—	m.p.–b.p.
ReF_7	−2 206	13.045	−1.47	—	259–m.p.
ReF_7	−244	−21.585	+9.91	—	m.p.–b.p.
$ReOF_4$	−3 888	11.88	—	—	323–m.p.
$ReOF_4$	−3 206	10.09	—	—	m.p.–b.p.
$ReOF_5$	−1 959	8.62	—	—	303–m.p.
$ReOF_5$	−1 679	7.727	—	—	m.p.–b.p.
Re_2O_2F	−3 437	10.36	—	—	m.p.–b.p.
Re_2O_7	−7 300	15.000	—	—	273–m.p.
Re_2O_7	−3 950	9.10	—	—	m.p.–b.p.
$RuCl_3$	−16 750	30.53	−4.63	—	298–1 000
$SO_3\alpha$	−2 680	11.44	—	—	273–m.p.
$SO_3\beta$	−2 860	11.97	—	—	273–m.p.
$SO_3\gamma$	−3 610	14.00	—	—	273–m.p.
SO_3	−2 230	9.90	—	—	m.p.–b.p.
SO_2Cl_2	−1 660	7.65	—	—	m.p.–b.p.
SbF_5	−2 364	8.567	—	—	282–416
$SbCl_3$	−3 460	2.81	3.88	−5.6	298–m.p.
$SbCl_3$	−3 770	29.48	−7.04	—	m.p.–b.p.
$SbCl_5$	−2 530	8.56	—	—	m.p.–350
$SbBr_3$	−2 860	7.97	—	—	435–561
SbI_3	−3 450	7.99	—	—	510–629
Sb_4O_6*	−10 360	12.195	—	—	742–839
Sb_4O_6†	−9 625	11.312	—	—	742–914
Sb_4O_6	−3 900	5.137	—	—	929–1 073
$ScCl_3$	−14 200	14.37	—	—	1 065–1 233
$ScBr_3$	−13 780	14.35	—	—	1 042–1 200
ScI_3	−13 340	14.17	—	—	1 010–1 180
SeF_4	−2 457	9.44	—	—	m.p.–b.p.
ScO_2	−6 170	21.40	−3.02	—	298–s.p.
$SiCl_4$	−1 572	7.64	—	—	273–333
SiI_4	−3 863	23.38	−5.0	—	m.p.–b.p.
$SnCl_4$	−1 925	7.865	—	—	298–b.p.
$SnBr_4$	−3 510	27.63	−6.5	—	303–b.p.
SnI_4	−3 990	10.08	—	—	298–m.p.
SnI_4	−2 975	7.666	—	—	m.p.–b.p.
SrF_2	−21 660	28.04	−5.03	—	m.p.–b.p.
$TaCl_5$	−6 275	34.305	−7.04	—	298–m.p.
$TaCl_5$	−2 975	8.68	—	—	m.p.–b.p.
$TaBr_5$	−7 320	34.85	−7.04	—	298–m.p.
$TaBr_5$	−3 260	8.14	—	—	m.p.–b.p.
TaI_5	−6 660	31.61	−7.04	—	298–m.p.
TaI_5	−3 955	7.72	—	—	m.p.–b.p.
Tc_2O_7	−7 205	18.28	—	—	298–m.p.
Tc_2O_7	−3 570	9.00	—	—	m.p.–b.p.
TeF_4	−3 174	9.093	—	—	298–m.p.
TeF_4	−1 787	5.640	—	—	m.p.–467

* cubic † orthorhombic

Table 8.14 HALIDES AND OXIDES—*continued*

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
TeF_6	−1 460	9.13	—	—	194–241
$TeCl_2$	−3 350	8.51	—	—	m.p.–b.p.
TeO_2	−13 940	23.51	−3.52	—	298–m.p.
$ThCl_4$	−12 900	14.30	—	—	974–1 043
$ThCl_4$	−7 980	9.57	—	—	1 043–1 186
$ThBr_4$	−9 630	11.73	—	—	903–951
$ThBr_4$	−7 550	9.56	—	—	955–1 126
ThI_3	−6 890	9.09	—	—	856–1 107
ThO_2	−34 890	10.87	—	—	2 500–2 900
TiF_4	−5 332	19.51	−2.57	—	298–s.p.
$TiCl_2$	−15 230	19.36	−2.51	—	298–m.p.
$TiCl_2$	−13 110	17.93	−2.51	—	m.p.–b.p.
$TiCl_3$	−9 620	21.47	−3.27	—	298–m.p.
$TiCl_4$	−2 919	25.129	−5.788	—	298–b.p.
$TiBr_4$	−3 706	27.08	−6.24	—	m.p.–b.p.
TiI_2	−12 500	16.90	−1.51	—	298–1 000
TiI_4	−3 054	7.576	—	—	430–643
TlF	−7 710	17.66	−2.18	—	298–m.p.
TlCl	−7 370	16.49	−2.11	—	298–m.p.
TlCl	−6 650	16.92	−2.62	—	m.p.–b.p.
TlBr	−7 420	16.18	−2.0	—	298–m.p.
TlBr	−6 840	18.26	−3.02	—	m.p.–b.p.
TlI	−7 270	15.85	−2.01	—	298–m.p.
TlI	−6 890	18.20	−3.02	—	m.p.–b.p.
UF_4	−16 400	22.60	−3.02	—	298–m.p.
UF_4	−15 300	29.05	−5.03	—	m.p.–b.p.
UF_6	−2 858	16.36	−1.91	—	273–s.p.
UCl_4	−11 350	23.21	−3.02	—	298–m.p.
UCl_4	−9 950	28.96	−5.53	—	m.p.–b.p.
UCl_6	−4 000	10.20	—	—	298–450
UBr_3	−16 420	22.95	−3.02	—	298–m.p.
UBr_3	−15 000	27.54	−5.03	—	m.p.–(b.p.)
UBr_4	−10 800	23.15	−3.02	—	298–m.p.
UBr_4	−8 770	27.93	−5.53	—	m.p.–b.p.
UI_4	−12 330	26.62	−3.52	—	298–m.p.
UI_4	−9 310	28.57	−5.53	—	m.p.–b.p.
UO_2	−33 120	25.69	−4.03	—	1 500–2 800
VF_5	−2 423	10.43	—	—	m.p.–b.p.
VCl_4	−2 875	25.56	−6.07	—	298–m.p.
$VOCl_3$	−1 921	7.70	—	—	298–b.p.
V_2O_5*	−7 100	5.05	—	—	m.p.–1 500
WF_6	−1 380	7.635	—	—	m.p.–b.p.
$WCl_6(\alpha)$	−3 996	9.615	—	—	458–503
$WCl_6(\beta)$	−3 588	8.795	—	—	503–554
WCl_4	−3 253	8.195	—	—	555–598
WCl_5	−3 670	9.50	—	—	413–m.p.
WCl_5	−2 760	7.72	—	—	m.p.–b.p.
$WCl_6\alpha$	−4 580	10.73	—	—	425–t.p.
$WCl_6\beta$	−4 080	9.73	—	—	t.p.–m.p.
WCl_6	−3.050	7.87	—	—	m.p.–b.p.
WOF_4	−3 605	10.96	—	—	298–m.p.
WOF_4	−3 125	9.69	—	—	m.p.–b.p.

* Apparent vapour pressures. V_2O_5 loses oxygen with increasing temperature.

Table 8.14 HALIDES AND OXIDES—*continued*

Substance	*A*	*B*	*C*	*D*	*Temp. range* K
WO_3	−24 600	15.63	—	—	1 000–m.p.
ZnF_2	−13 650	26.90	−5.03	—	m.p.–b.p.
$ZnCl_2$	−8 500	16.61	−1.50	—	298–m.p.
$ZnCl_2$	−8 440	26.37	−5.03	—	m.p.–b.p.
$ZnBr_2$	−7 120	16.21	−2.01	—	298–m.p.
ZnI_2	−6 450	14.70	−1.76	—	298–m.p.
ZnS	−13 980	8.98	—	—	970–1 280
ZrF_4	−14 700	30.80	−5.03	—	298–s.p.
$ZrCl_4$	−5 400	11.765	—	—	480–689
$ZrBr_4$	−6 780	19.60	−1.76	−1.65	298–s.p.
ZrI_4	−7 680	20.87	−2.164	−1.344	298–s.p.

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9 Physical properties of molten salts

In the following tables are given densities, electrical conductivities, surface tensions and coefficients of viscosity of pure molten salts, molten binary salt systems and other ionic melts. For comprehensive data and treatment, reference should be made to G. J. Janz, 'Molten Salts Handbook', 1967, Academic Press, New York/London.

Table 9.1 DENSITY OF PURE MOLTEN SALTS

The density of most pure molten salts varies almost linearly with temperature, and may be represented by the equation:

$$d_t = a - 10^{-3} \cdot bt$$

where d_t is the density in g cm^{-3}, a and b are constants, and t is the temperature in °C over appreciable ranges of temperature. Values of the constants and the appropriate temperature ranges are given below. Principal references are in **bold type**.

Substance	*a*	*b*	*Range of observations** °C	*References*
AgBr	6.025	1.04	m.p. to 820	**91, 60, 33,** 10
AgCl	5.257	0.849	467 to 637	**140, 97, 91,** 33
$AgClO_3$	4.2626	1.742	m.p. to 250	**18**
AgI	6.139	1.01	600 to 800	**33**
$AgNO_3$	4.167	1.00	m.p. to 410	**108, 100, 97, 18,** 112, 105, 93, 34, 10
$AlBr_3$	2.875	2.314	m.p. to 225	**89, 88, 38**
$AlCl_3$	1.805	2.5	194 to 250	**38**
AlI_3	3.70	2.5	m.p. to 250	**38**
Al_2O_3	5.259	1.127	2102 to 2352	**121**
$AsBr_3$	3.455	2.6	50 to 100	**96, 34,** 14
$AsCl_3$	2.205	2.18	m.p. to 130	**87, 8,** 1
AsF_3	$d_1 = 2.6659 = 3.839 \cdot 10^{-3}t + 4.35 \cdot 10^{-8}t^2$		0 to 60	**8**
		$d_{25} = 3.01$		**78**
AsF_5	2.047	5.34	m.p. to −53	**68**
BBr_3		$d_o = 2.650$		**15**
BCl_3		$d_{11} = 1.349$		**52**
BI_3		$d_{50} = 3.3$		**12**
B_2O_3	1.609	0.0867	1030 to 1310	**101, 114,** 19
$BaBr_2$		$d_{850} = 4.00$		**102**
$BaCl_2$	3.8292	0.6813	966 to 1081	**122,** 104, 103, 85, 19
BaF_2	5.502	0.999	1327 to 1727	**123**
$Ba(NO_2)_2$	3.448	0.70	—	**124**
$BeCl_2$	1.976	1.1	430 to 475	**47**
$BiBr_3$	5.248	2.6	270 to 330	**34**
$BiCl_3$	4.42	2.20	240 to 350	**120, 40, 34, 23**
$Bi_2(MoO_4)_3$		$d_{723} = 5.170$		**125**
$CaCl_2$	2.4108	0.4225	787 to 950	**122,** 99, 86, 22, 19, 92
CaF_2	3.072	0.391	1367 to 2027	**123,** 111

Table 9.1 DENSITY OF PURE MOLTEN SALTS—*continued*

Substance	*a*	*b*	*Range of observations** °C	*References*
$CdBr_2$	4.688	1.08	m.p. to 720	**91**
$CdCl_2$	3.858	0.825	m.p. to 800	**102, 91**
CdI_2	4.828	1.12	m.p. to 700	**102**
CeF_3	5.997	0.936	1427 to 1927	**123**
CsBr	3.911	1.22	m.p. to 860	**113, 34**
CsCl	3.478 5	1.065	667 to 907	**113, 34, 140**
CsF	4.548 9	1.280 6	712 to 912	**122, 34**
CsI	3.918	1.18	645 to 855	**113, 34**
$CsNO_3$	3.302 3	$1.160\,0_5$	415 to 491	**126, 34**
Cs_2SO_4	2.956	0.586	1027 to 1477	**34**
Cu_2Cl_2	4.010	0.79	m.p. to 585	**47**
Cu_2S	6.76	0.75	1150 to 1400	**119**
FeS	3.85	0	1250 to 1450	**119**
$GaBr_2$	3.753	1.69	160 to 175	**127**
$GaBr_3$	3.507	2.95	m.p. to 230	**70**
$GaCl_2$	2.652	1.36	166 to 177	**127**
$GaCl_3$	2.223	2.05	m.p. to 195	**116, 70, 9**
Ga_2I_4	4.380	1.688	181 to 265	**128**
Ga_2I_6	4.128	2.377	185 to 255	**128, 70**
$HfCl_4$		$d_{435} = 1.71$		**129**
$HgBr_2$	5.888 9	3.233 1	238 to 319	**130, 26**
$HgCl_2$	5.157 7	2.862 4	277 to 304	**130, 26**
Hg_2Cl_2	8.00	4.0	m.p. to 580	**47**
HgI_2	6.060 3	3.235 1	259 to 354	**130, 26, 107**
ICl	3.186	3.0	m.p. to 100	**8, 5**
$InBr_3$	3.674	1.5	450 to 530	**48**
InCl	4.055	1.4	269 to 365	**48**
$InCl_2$	3.43	1.6	268 to 437	**48**
$InCl_3$	3.37	2.1	597 to 666	**48**
InI_3	4.135	1.5	230 to 360	**48**
KBr	2.733	0.825 3	747 to 927	**113, 102, 140**
KCl	1.976 7	0.583 1	777 to 947	**146, 140, 102, 110, 104, 98**
K_2CO_3	2.293 4	0.442	907 to 1007	**141**
$K_2Cr_2O_7$	2.563 3	0.695	420 to 535	**142**
KF	2.468 5	0.651 5	881 to 1037	**122, 34**
$KHSO_4$	2.232	0.767	207 to 230	**94**
KI	3.098 5	0.955 7	682 to 904	**110, 102**
K_2MoO_4	2.992 2	0.549 1	935 to 988	**134, 34**
KNO_2	2.005	0.700	440 to 500	**106, 124**
KNO_3	2.116	0.729	m.p. to 600	**106, 102, 77, 55, 34, 21, 18, 124, 126**
KOH	1.893	0.44	400 to 600	**45, 37**
KPO_3	2.455	0.43	990 to 1200	**34**
K_2SO_4	2.472	0.545	1100 to 1300	**34**
K_2WO_4	3.844 7	0.727 3	944 to 1053	**135, 34**
$LaBr_3$	5.008 9	0.096 0	796 to 912	**122**
$LaCl_3$	3.877 3	0.777 4	873 to 973	**122, 47**
LaF_3	5.607	0.682	1477 to 2177	**123**
LiBr	2.888	0.652	m.p. to 740	**113, 16, 60**
LiCl	1.766 0	0.432 8	627 to 777	**110, 102, 98, 34, 16**
$LiClO_4$	2.171 2	0.622 3	—	**136**
Li_2CO_3	2.10	0.373	737 to 847	**141**

Table 9.1 DENSITY OF PURE MOLTEN SALTS—*continued*

Substance	*a*	*b*	*Range of observations** °C	*References*
LiF	2.224 3	0.490 2	876 to 1 047	**122**, 34
LiI	3.540	0.918	m.p. to 670	**113**
Li_2MoO_4	3.200 8	0.415 2	781 to 963	**134**
$LiNO_3$	1.924	0.548	m.p. to 550	**34, 18**
Li_2SO_4	2.352 9	0.407	860 to 1 214	**143**, 34
Li_2WO_4	4.905 5	0.805 3	764 to 901	**135**
$MgCl_2$	1.894	0.302	727 to 967	**144**, 47, 83, 133
MgF_2	3.092	0.524	1 377 to 1 827	**123**
$MnCl_2$	2.639	0.44	650 to 850	**137**
MoF_6	2.637	4.91	m.p. to 34	**64**
MoO_3	4.443 6	1.498 3	821 to 918	**134**, 109
Na_3AlF_6	3.036	0.94	m.p. to 1 100	*See* Binary System Na_3AlF_6–NaF
NaBr	2.952	0.817	m.p. to 945	**113, 34, 16**
NaCl	1.991 1	0.543	803 to 1 030	**102, 147, 140, 146, 110**, 98
Na_2CO_3	2.357	0.449	867 to 1 007	**141**
NaF	2.502	0.560	997 to 1 057	**34**, 45
NaI	3.368	0.949	m.p. to 915	**113, 102, 34**
Na_2MoO_4	3.235	0.629	700 to 1 400	**35**, 109
$NaNO_2$	2.004	0.690	280 to 500	**106, 102**
$NaNO_3$	2.124 8	0.715	317 to 427	**106, 100, 102, 77, 34, 21, 18**
NaOH	1.937 4	0.478 4	320 to 450	**145**
$NaPO_3$	2.545	0.44	905 to 1 010	**34, 19**
Na_2SO_4	2.495	0.48	900 to 1 050	**34, 16**
Na_2WO_4	4.519 9	0.906 7	714 to 880	**135**, 35, 16
$NdBr_3$	4.762 6	0.777 9	695 to 860	**122**
NH_4NO_3	1.536	0.60	170 to 200	**118**
$Ni(CO)_4$	$d_l = 1.356\,1 - 2.213 \cdot 10^{-3} t - 4.10^{-6} t^2$		0 to 36	**13**
$OsSO_4$	4.504	4.17	43 to 150	**62**
PBr_3	2.924	2.48	0 to 200	**8, 1**
PCl_3	1.612	1.86	−80 to 75	**87, 29, 8**, 39, 1
$PbBr_2$	5.036	1.45	377 to 497	**91, 21**
$PbCl_2$	5.702	1.5	502 to 710	**91**, 85, 61, 60, 21
$PbCl_4$		$d_0 = 3.18$		**50**
PbI_2		$d_{383} = 5.625$		**10**
$PbMoO_4$		$d_{1107} = 5.213$		**125**
RbBr	3.446 4	1.072	700 to 910	**113, 34**
RbCl	2.880	0.883	m.p. to 925	**113, 47**, 34
RbF	3.707	1.011	820 to 1 005	**34**
RbI	3.638	1.14	655 to 905	**113, 34**
$RbNO_3$	2.782	0.97	350 to 550	**34**
Rb_2SO_4	3.260	0.665	1 100 to 1 310	**34**
ReF_6	3.776	8.51	m.p. to 47.6	**79, 76**
Re_2O_7		$d_{331} = 4.30$		**67**
ReO_3Cl	3.94	4.0	16 to 37	**67**
$ReOF_4$	3.921	5.1	40 to 60	**79**
S_2Cl_2	1.710	1.57	0 to 136	**87, 8**, 2
$SOCl_2$	1.677	1.97	0 to 69	**8**
SO_2Cl_2	1.708	2.11	0 to 70	**8**
$SbBr_3$		$d = 3.691$ at m.p.		**81, 31**, 27, 6, 3
$SbCl_3$†	2.849	2.268	m.p. to 165	**84**, 54, 41, 20, 3
$SbCl_5$	2.392	2.04	m.p. to 80	**65, 54**, 32, 17

Table 9.1 DENSITY OF PURE MOLTEN SALTS—*continued*

Substance	*a*	*b*	*Ranges of observations* °C*	*References*
SbF_5		$d_{22.7}=2.993$		17
$ScCl_3$		$d_{1000}=1.63$		47
Se_2Cl_2		$d_{25}=2.774$		51
SeF_4		$d=2.8$ at room temp.		56
SeF_6		$d=2.3$ at m.p.		69
$SeOBr_2$		$d_{50}=3.38$		36
$SeOCl_2$	2.478	2.08	m.p. to 80	63, 57, 43
$SeOF_2$		$d=2.7$ at room temp.		56
$SiBr_4$	2.812	2.63	—	8
$SiCl_4$	1.523	2.08	−30 to 60	87, 8, 1
$SnCl_2$	3.6739	1.253	247 to 407	47, 34
$SnCl_4$	2.273	2.62	−19 to 113	8, 1
SnI_4	4.145	2.45	145 to 275	53
$SrCl_2$	3.2318	0.5781	893 to 1037	122, 19
SrF_2	4.579	0.751	1477 to 1927	123
$TeCl_4$	2.965	1.64	230 to 430	59
TeF_6	2.442	6.02	m.p. to −10	69
$ThCl_4$		$d=3.32$ at about 830		47
$TiBr_4$	3.043	2.25	40 to 120	115
$TiCl_4$	1.761	1.72	m.p. to 135	73, 71, 8, 1, 90, 58
TiI_4	3.755	2.19	166 to 270	70
TlBr	6.908_4	1.922_0	493 to 750	131
TlCl	6.402	1.80	m.p. to 640	47
$TlNO_3$	5.2672	1.75	210 to 430	34
UCl_4	2.50	1.7	—	138
V_2O_5		$d_{1000}=2.5$		139
$VOCl_3$	1.865	1.83	0 to 125	25, 11, 8, 4
WF_6	3.529	5.84	m.p. to 19	64
YCl_2	2.87	0.5	m.p. to 845	47
$ZnBr_2$	3.8512	0.959	397 to 627	144, 72
$ZnCl_2$	2.693	0.515	m.p. to 630	117, 47, 61
$ZrCl_4$		$d_{448}=1.54$		129

* Melting points will be found in Table 9.3.

† Between m.p. and 375 °C density of $SbCl_3$ given by:
$d_t=2.622-2.268\cdot10^{-3}\ (t-100)-0.32\cdot10^{-6}\ (t-100)^2$.
Between 375 °C and 505 °C:
$d_t=2.622-2.268\cdot10^{-3}\ (t-100)-0.32\cdot10^{-6}\ (t-100)^2+8.8\cdot10^{-12}(t-100)^4-3.4\cdot10^{-14}\ (t-100)^5$.

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Table 9.2. DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS
The density ($g\,cm^{-3}$) at temperature t(°C) and composition p(wt.%) of the first-named constituent is given as d_t, or the constants a and b in the equation $d_t = a - 10^{-3}\,bt$ or A, B and C in the equation $d_t = 10^6 At^{-2} - 10^3 Bt^{-1} + C$ are given together with the temperature range r(°C). Principal references are in **bold type.**

AgBr–AgCl	*p*	0	27.8	46.9	71.6	100		
Ref. 25	*a*	5.262	5.523	5.678	5.832	6.025		
	b	0.94	1.08	1.12	1.07	1.04		
	r	480–630	440–580	420–590	420–580	440–600		
AgBr–KBr	*p*	0	50.8	70.4	85.7	100	64.6	
Ref. 64, 25, 7	*a*	2.706	3.686	4.376	5.156	6.023	4.077	
	b	0.80	0.98	1.03	1.12	1.05	1.03	
	r	750–800	593–700	380–600	380–600	440–600	546–629	
AgBr–LiBr	*p*	68.5						
Ref. 65	*a*	4.504						
	b	0.877						
	r	517–555						
AgBr–NaBr	*p*	64.6						
Ref. 66	*a*	4.311						
	b	0.9						
	r	607–619						
AgBr–RbBr	*p*	53.2						
Ref. 67	*a*	4.470						
	b	1.23						
	r	514–624						
AgCl–$AgNO_3$	*p*	0	9.00	12.5	15.5	20.0	30.0	40.0
Ref. 33	*a*	4.167	4.242	4.279	4.297	4.338	4.431	4.497
	b	1.00	1.00	1.00	1.00	1.00	1.00	0.90
	r				310–330			
AgCl–KCl	*p*	0	63.8	80.3	88.9	100		
Ref. 25, 7	*a*	1.988	3.286	4.001	4.463	5.263		
	b	0.60	0.88	0.96	0.95	0.94		
	r	785–880	560–745	385–640	433–670	480–630		
AgCl–$PbCl_2$	*p*	0	11.0	19.4	24.7	31.0	41.0	66.9
Ref. 25	*a*	5.702	5.660	5.634	5.582	5.543	5.520	5.387
	b	1.50	1.45	1.42	1.34	1.28	1.26	1.08
	r	516–710	520–700	470–680	445–670	444–680	380–700	478–660
AgI–$AgNO_3$	*p*	20	30	40	50	60	70	
Ref. 54, 30	*a*	4.53	4.97	5.12	5.31	5.44	5.53	
	b	1.2	2.2	2.1	2.1	1.8	1.5	
	r			about 150–300				
$AgNO_3$–$Cd(NO_3)_2$	*p*	32.4	37.0	46.8	57.2	68.4	74.2	
	a	1.721	1.762	1.843	1.930	2.003	2.032	
Ref. 50	*b*	1.01	1.05	1.10	1.15	1.15	1.14	
	r	210–290	160–290	160–290	190–290	190–290	210–290	
$AgNO_3$–HgI_2	*p*	13.8	19.9	27.2	35.9	46.6	52.8	67.9
Ref. 49	*a*	5.826	5.732	5.584	5.364	5.188	5.074	4.930
	b	1.58	1.46	1.46	1.46	1.40	1.34	1.28
	r	160–240	160–240	100–240	120–240	100–240	100–240	120–240
$AgNO_3$–KNO_3	*p*	15.7	29.6	41.9	52.8	62.7	79.7	93.8
Ref. 57, 46	*a*	2.284	2.534	2.654	2.856	2.986	3.516	3.765
	b	0.76	0.97	0.84	0.89	0.76	1.08	0.85
	r	350–400	300–400	250–400	250–400	250–400	170–350	200–400
$AgNO_3$–$NaNO_3$	*p*	0	10	20	30	40	60	80
Ref. 37	*a*	2.124	2.226	2.357	2.486	2.616	2.974	3.439
	b	0.70	0.71	0.77	0.79	0.79	0.70	0.90
	r				about 290–370			

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$AgNO_3$–NH_4NO_3	p	0	5	10				
Ref. 58	d_{170}	1.432	1.479	1.529				
	d_{180}	1.426	1.474	1.523				
$AgNO_3$–$TlNO_3$	p	25	45	50	60	75	90	100
Ref. 26	d_{100}	—	4.671	4.630	4.554	—	—	—
	d_{150}	—	4.575	4.526	4.435	—	—	—
	d_{200}	4.638	4.452	4.410	4.319	4.183	4.074	
	d_{225}	4.579	4.406	4.351	4.261	4.132	4.024	3.922
$AlBr_3$–$HgBr_2$	p	59.7	65.4	71.2	74.9	80.5	89.6	100
Ref. 21, 4	d_{110}	3.577	3.415	3.276	3.173	3.030	2.827	2.624
	d_{140}	3.504	3.359	3.202	3.097	2.961	2.755	2.555
$AlBr_3$–KBr	p	81.8	83.2	84.7	86.2	87.5	88.0	
Ref. 28, 4	d_{110}	2.818	2.815	2.810	2.804	2.798	2.790	
	d_{140}	2.775	2.771	2.764	2.755	2.749	2.741	
$2AlBr_3$–KCl	a	2.846						
Ref. 23	b	1.445						
	r	80–170						
$AlBr_3$–NaBr	p	83.8	84.7	85.6	86.8	87.9	88.9	
Ref. 28	d_{120}	2.827	2.820	2.817	2.809	2.798	2.786	
	d_{140}	2.797	2.792	2.787	(2.777)	2.767	2.756	
$2AlBr_3$.NaBr	a	3.005						
Ref. 23	b	1.5						
	r	110–170						
$AlBr_3$–NH_4Br	p	84.5	87.9	89.0	89.4	90.8	100	
Ref. 21	a	2.842	2.865	2.877	2.881	2.889	2.877	
	b	1.30	1.40	1.45	1.50	1.60	2.30	
	r				110–150			
$2AlBr_3$.NH_4Br	a	2.848						
Ref. 23	b	1.36						
	r	110–160						
$AlBr_3$–$SbBr_3$	p	0	34.1	42.5	67.4	71.9	91.3	100
Ref. 20, 4	d_{100}	3.697	3.402	3.318	3.034	2.971	2.737	2.644
	d_{140}	3.594	3.311	3.224	2.941	2.881	2.641	2.556
$AlBr_3$.$SbBr_3$	a	3.541						
Ref. 32, 23	b	2.3						
	r	80–170						
$AlBr_3$.$SbBr_3$–$AsBr_3$	p	0	16.3	59.9	67.9	77.3	86.8	100
	d_{85}	3.232	3.231	3.286	3.304	3.310	3.330	3.346
Ref. 32	d_{100}	3.193	3.191	3.247	3.263	3.274	3.295	3.313
$AlBr_3$–$ZnBr_2$	p	70.5	74.5	77.7	82.5	85.0	88.4	100
Ref. 20	d_{100}	3.014	(2.957)	2.914	2.849	2.811	2.768	2.644
	d_{130}	2.915	2.850	2.811	2.740	2.704	2.657	2.534
$2AlBr_3$.$ZnBr_2$	t	100	140	180				
Ref. 23	d	3.01	2.93	2.81				
$AlCl_3$–KCl**	p	50.4	53.7	62.5	64.2	71.2	76.1	84.2
Refs. 63, 45, 29,	a	1.787	1.785	1.755	1.937	1.859	1.819	1.820
19	b	0.590	0.605	0.600	0.935	0.902	0.789	0.850
	r	600–800	600–800	600–800	260–350	240–280	190–270	175–225
$AlCl_3$–LiCl**	p	75.9	79.3	82.5	85.4	87.9	90.4	
Ref. 63, 19	a	1.735	1.737	1.757	1.759	1.768	1.741	
	b	0.77	0.68	0.80	0.84	0.90	0.80	
	r	180–330	175–225	175–225	175–225	175–225	175–225	

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$AlCl_3$–NaBr	*p*	58.6	61.0	65.7	70.3	74.8	79.3	
Ref. 63	*a*	2.158	2.119	2.064	2.017	1.979	1.944	
	b	0.92	0.86	0.92	0.96	1.02	1.12	
	r		175–225				200–275	
$AlCl_3$–NaCl**	*p*	69.5	71.9	73.5	75.8	79.5	84.1	90.1
Ref. 63, 45, 16, 19	*a*	1.848	1.858	1.839	1.829	1.792	1.787	1.810
	b	0.812	0.910	0.849	0.844	0.715	0.840	1.04
	r	220–280	160–210	150–210	150–210	150–210	175–225	175–225
$AlCl_3.NH_4Cl$	*t*	284	293	311	315	324	354	
Ref. 19	*d*	1.475	1.470	1.445	1.440	1.425	1.420	
$AlCl_3$–RbCl	*p*	71.9	76.7					
Ref. 63	*a*	1.992	1.975					
	b	0.96	1.00					
	r	175–225						
AlF_3–Na_3AlF_6*	*p*	0	5	10	15	20	25	30
Ref. 62, 38, 31, 24,	d_{1000}	2.096	2.078	2.048	2.015	1.977	1.930	1.873
22, 15, 14, 13,	d_{1100}	2.002	1.987	1.965	1.935	1.894	1.839	1.775
10, 9, 6								
Al_2O_3–Na_3AlF_6	*p*	0	2.5	5	7.5	10	12.5	15
Ref. 62, 38, 14,	d_{1000}	2.096	2.076	2.060	2.048	2.039	2.033	2.028
31, 6	d_{1100}	2.002	1.985	1.974	1.966	1.960	1.957	1.954
B_2O_3–BaO	*p*	20.7	30.0	39.8	49.2	59.7	67.9	
Ref. 44	*a*	4.038	5.006	4.780	4.422	3.704	3.392	
	b	—	1.32	1.40	1.34	0.96	0.96	
	r	1 120	1 000–1 200	1 000–1 100	850–1 100	850–1 000	850–1 100	
B_2O_3–CaO	*p*	55.3	59.8	62.8	67.9	70.2	73.3	
Ref. 44	*a*	2.926	2.901	2.876	2.871	2.932	2.844	
	b	0.44	0.45	0.46	0.51	0.59	0.56	
	r	1 160–1 200	1 110–1 210	1 140–1 190	1 100–1 200	1 060–1 100	900–1 200	
B_2O_3–K_2O	*p*	51.5	55.7	65.6	75.3	84.9	94.8	98.5
Ref. 40	*a*	2.690	2.534	2.412	2.185	2.057	1.855	1.737
	b	0.905	0.687	0.500	0.310	0.295	0.255	0.217
	r	900–1 000	800–1 000	700–1 000	800–1 000	700–1 000	600–1 000	500–1 000
B_2O_3–Li_2O	*p*	71.3	85.2	89.4	93.5	97.2	100.0	
Ref. 40	*a*	2.340	2.400	2.281	2.103	1.901	1.662	
	b	0.467	0.467	0.402	0.335	0.260	0.153	
	r	800–1 000	800–1 000	700–1 000	600–1 000	600–1 000	600–1 200	
B_2O_3–Na_2O	*p*	64.0	69.2	77.6	85.8	94.4	99.1	100.0
Ref. 40	*a*	2.540	2.778	2.413	2.137	1.898	1.759	1.662
	b	0.57	0.86	0.435	0.278	0.235	0.222	0.153
	r	900–1 000	700–800	700–1 000	700–1 000	600–1 100	600–1 000	600–1 200
B_2O_3–SrO	*p*	44.9	49.6	56.8	61.6	65.2	70.0	
Ref. 44	*a*	3.472	3.513	3.402	3.230	3.124	2.948	
	b	0.43	0.56	0.61	0.57	0.57	0.51	
	r	1 150–1 200	1 120–1 220	960–1 100	950–1 100	950–1 100	920–1 120	
$BaBr_2$–KBr	*p*	39.2	45.1	55.5	62.5	73.0	82.2	88.2
Ref. 41	*a*	3.318	3.324	3.558	3.720	3.932	4.117	4.425
	b	0.937	0.849	0.896	0.930	0.906	0.875	1.02
	r	660–850	640–850	630–850	630–850	630–850	690–850	750–850
$BaCl_2$–$CdCl_2$	*p*	0	18.99	39.00	57.35	100		
Ref. 25, 1	*a*	3.870	3.996	4.018	4.069	3.672		
	b	0.84	0.93	0.93	0.96	0.52		
	r	582–725	597–700	580–700	600–690	above 1 000		

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS *–continued*

$BaCl_2$–KCl	p	20.4	29.6	47.4	58.2	70.1	82.8	91.4
Ref. 43	a	2.199	2.237	2.554	2.744	3.035	3.268	3.456
	b	0.64	0.59	0.63	0.70	0.77	0.65	0.68
	r	790–900	790–890	790–890	800–890	790–880	820–910	880–940
$BaCl_2$–$MgCl_2$	p	9.95	25.0	50.2	75.1	90.0		
Ref. 69, 35, 70	a	2.073	2.333	2.835	3.400	(3.642)		
	b	0.36	0.47	0.64	0.75	0.71		
	r			800–900				
$BaCl_2$–NaCl	p	44.0	54.4	62.7	69.7	75.3	80.1	84.4
Ref. 71, 17	d_{725}	—	2.204	2.350	2.491	2.620	—	—
	d_{750}	—	2.192	2.334	2.471	2.590	—	—
	d_{775}	1.992	2.180	2.318	2.452	2.560	2.650	2.760
	d_{800}	1.986	2.169	2.302	2.432	2.531	2.616	2.730
$BaCl_2$–NH_4NO_3	p	0	1.5					
Ref. 58	d_{180}	1.426	1.436					
$BaCl_2$–$PbCl_2$	p	0	10.71	15.57	24.83	100		
Ref. 25, 1	a	5.702	5.430	5.356	5.156	3.662		
	b	1.50	1.35	1.36	1.27	0.52		
	r	516–710	565–700	575–690	660–710	above 1 000		
BaF_2–Na_3AlF_6	p	0	33.1	55.4	71.5			
Ref. 15, 10	a	3.069	3.429	3.978	3.804			
	b	0.96	0.838	0.996	0.447			
	r	1 020–1 130	920–1 175	960–1 155	910–1 120			
BaF_2–NaF	p	0	45.2	67.5	80.7			
Ref. 15	a	2.590	3.291	3.739	4.195			
	b	0.628	0.626	0.600	0.624			
	r	1 010–1 120	955–1 160	970–1 165	955–1 180			
$Ba(NO_2)_2$–	p	5.7	13.4					
$Ba(NO_3)_2$	d_{300}	3.240	3.243					
Ref. 72	d_{320}	3.226	3.212					
	d_{340}	3.212	3.216					
$Ba(NO_2)_2$–KNO_2	p	59.0	73.7	80.0	86.8	92.5	97.6	
Ref. 72	d_{280}	2.274	2.492	—	—	—	3.154	
	d_{320}	2.245	2.458	2.615	2.780	2.950	3.126	
	d_{340}	2.132	2.440	2.577	2.750	2.921	3.099	
	d_{360}	2.218	2.422	2.577	2.750	2.921	3.099	
$Ba(NO_3)_2$–KNO_3	p	9.54	25.8	33.1	39.7	45.9	51.5	57.0
Ref. 72, 36, 73	d_{340}	1.914	2.014	2.068	2.118	—	—	—
	d_{380}	1.884	1.984	2.036	2.088	2.143	2.201	—
	d_{420}	1.885	1.953	2.004	2.056	2.111	2.168	2.228
	d_{460}	—	—	1.974	2.026	2.080	2.136	2.196
$Ba(NO_3)_2$–	p	0	2.5	5.0				
NH_4NO_3	d_{170}	1.432	1.453	1.474				
Ref. 58	d_{180}	1.426	1.447	1.466				
BaO–SiO_2	p	22.1	39.0	52.3	63.0	72.0		
Ref. 74	a	2.580	3.016	3.401	3.748	4.044		
	b	0.000	0.048	0.068	0.075	0.080		
	r			1 600–1 950				
BeF_2–LiF	p	51.5						
Ref. 75	a	2.09						
	b	0.27						
	r	500–800						
Bi–$BiBr_3$	p	52.1						
Ref. 68	d_{543}	6.69						

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

Bi-$BiCl_3$	p	0	7.5	14.7	19.7	23.8	97.9	100
Ref. 61	a	4.42	4.61	4.87	5.07	5.24	10.39	10.39
	b	2.20	2.06	2.08	2.13	2.15	1.29	1.29
	r	240–330	290–400	270–420	290–450	310–440	330–440	310 440
$CaCl_2$–KCl	p	0	20	40	50	60	80	100
Ref. 8	d_{800}	1.495	1.573	1.671	1.725	1.780	1.896	2.057
	d_{900}	1.434	1.517	1.613	1.667	1.734	1.850	2.009
$CaCl_2$–$MgCl_2$	p	22.6	27.7	42.6	59.4	76.6		
Ref. 35	a	2.16	2.115	2.217	2.319	2.365		
	b	0.47	0.40	0.44	0.48	0.45		
	r	723–895	753–907	728–886	730–902	746–898		
$CaCl_2$–NaCl**	p	17.5	32.3	44.9	65.5	74.0	88.5	94.5
Ref. 71, 27, 18, 8	d_{625}	—	—	—	1.899	1.944	—	—
	d_{700}	—	—	1.767	1.855	1.912	2.005	—
	d_{775}	1.612	1.679	1.730	1.830	1.879	1.974	2.013
	d_{850}	1.575	1.646	1.693	1.798	1.846	1.944	1.985
CaF_2–CaO	p	92.9	94.6	95.3	97.1	98.6	100	
Ref. 53	d_{1545}	2.63	2.50	2.53	2.59	2.68	2.75	
CaF_2–Na_3AlF_6	p	0	10	20	30	40	50	
Ref. 38, 31, 15	d_{1000}	2.096	2.162	2.223	2.283	2.334	2.366	
	d_{1100}	2.002	2.070	2.135	2.200	2.256	2.294	
CaF_2–NaF	p	0	26.9	48.0	65.0			
Ref. 15	a	2.602	2.692	2.804	2.929			
	b	0.64	0.58	0.57	0.54			
	r	1 010–1 120	930–1 185	870–1 165	1 050–1 170			
$Ca(NO_3)_2$–	p	0	5	10				
NH_4HO_3	d_{170}	1.432	1.460	—				
Ref. 58	d_{180}	1.426	1.453	1.480				
CaO–SiO_2	p	28.6	38.4	48.4	58.5			
Ref. 74	a	2.578	2.651	2.758	2.840			
	b	0.066	0.064	0.084	0.103			
	r			1 600–1 950				
$CdBr_2CdCl_2$	p	0	38.55	55.46	73.64	100		
Ref. 25	a	3.870	4.138	4.255	4.390	4.687		
	b	0.84	0.90	0.91	0.93	1.08		
	r	582–725	580–680	590–710	606–705	580–720		
$CdCl_2$–CdI_2	p	0	14.2	33.2	59.9	100		
Ref. 41	a	4.828	4.638	4.367	4.187	3.839		
	b	1.12	1.06	0.88	0.87	0.80		
	r	380–700	360–700	440–700	520–700	560–700		
$CdCl_2KCl$	p	0	44.77	62.10	78.10	92.36	100	
Ref. 25, 7	a	1.988	2.495	2.791	3.176	3.625	3.870	
	b	0.60	0.72	0.82	0.95	0.96	0.84	
	r	above 750	604–750	460 680	464 680	534–700	582–725	
$CdCl_2$–LiCl	p	0	59.1	81.2	92.9	100		
Ref. 41	a	1.731	2.572	3.245	3.593	3.839		
	b	0.382	0.577	0.845	0.825	0.800		
	r	600–750	560–750	510–750	520 -750	560–750		
$CdCl_2$ · NaCl	p	0	62.08	71.38	79.64	85.23	91.66	100
Ref. 25, 7	a	2.053	2.896	3.090	3.315	3.543	3.678	3.870
	b	0.63	0.83	0.86	0.92	1.04	0.95	0.84
	r	above 800	580–690	500–690	570 -680	540–680	580–700	582–725

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS —*continued*

$CdCl_2$–$PbCl_2$	*p*	0	27.62	52.14	75.66	85.40	100	
Ref. 25	*a*	3.870	4.305	4.726	5.222	5.402	5.702	
	b	0.84	1.02	1.18	1.39	1.43	1.50	
	r	582–725	540–680	515–700	480–680	545–680	510–710	
CdI_2–KI	*p*	0	28.0	52.5	68.8	81.6	92.6	100
Ref. 41	*a*	3.108	3.469	3.769	4.120	4.431	4.645	4.828
	b	0.96	1.09	1.12	1.22	1.29	1.17	1.12
	r	680–800	540–800	400–800	190–700	300–700	360–700	380–700
$Cd(NO_3)_2$–KNO_3	*p*	50.0	55.7	65.7	74.1	81.2		
Ref. 50	*a*	2.436	2.475	2.583	2.689	2.820		
	b	0.92	0.89	0.93	0.93	0.95		
	r	260–300	220–300	200–300	180–300	200–300		
Ce–$CeCl_3$	*p*	0.28	0.57	1.14	2.31	3.50	4.70	
Ref. 76	d_{850}	3.165 5	3.169 5	3.180 0	3.205 5	3.239 0	3.287 5	
	d_{900}	3.127 5	3.132 7	3.144 0	3.170 0	3.204 1	3.249 0	
	d_{950}	3.087 7	3.093 2	3.104 0	3.133 3	3.174 0	3.228 8	
Cu_2Cl_2–KCl	*p*	0	11.49					
Ref. 5	d_{800}	1.51	1.62					
Cu_2S–FeS	*p*	0	50	100				
Ref. 60	*a*	3.85	5.10	6.76				
	b	—	0.62	0.75				
	r	1 250–1 450	1 100–1 500	1 150–1 400				
FeO–SiO_2	*p*	73.7	78.3	82.8	88.1	91.5	95.7	100
Ref. 55	d_{1300}	3.67	3.81	4.00	4.16	4.32	4.61	4.90
KBr–KNO_3	*p*	0	17.2	37.0	54.1	70.2	86.9	100
Ref. 41	*a*	2.116	2.186	2.285	2.415	2.476	2.635	2.725
	b	0.729	0.714	0.727	0.779	0.730	0.801	0.794
	r	330–600	330–600	340–600	440–600	530–800	650–800	740–800
KBr–NaCl	*p*	67.2	100					
Ref. 41	*a*	2.447	2.725					
	b	0.723	0.794					
	r	750–800	740–800					
KBr–TlBr	*p*	5.7	15.2	37.0	41.4	57.6	60.5	74.6
Ref. 77	*a*	6.493_5	6.908_4	—	5.732_8	—	—	3.978_7
	b	1.934_2	3.421_4	—	3.084_1	—	—	1.893_6
	A	—	—	1.781_6	—	3.218_3	6.425_3	—
	B	—	—	3.878_9	—	6.631_9	14.160_5	—
	C	—	—	4.192_8	—	6.087_0	10.347_8	—
	r	490–628	584–732	707–759	750–799	721–798	747–857	758–797
KBr–$ZnSO_4$	*p*	34.7	41.0	42.6	55.2	59.6	63.9	68.9
Ref. 42, 34	*a*	3.090	3.003	2.985	3.105	2.939	2.940	2.965
	b	0.46	0.40	0.42	0.80	0.52	0.60	0.74
	r				500–550			
KCl–KI	*p*	0	2.8	7.8	13.3	26.8	41.2	64.4
Ref. 52	*a*	3.098	3.030	2.914	2.873	2.684	2.498	2.274
	b	0.956	0.930	0.864	0.890	0.826	0.755	0.690
	r	680–900	680–900	710–900	640–910	620–900	680–920	710–900
KCl–KNO_3	*p*	6.4	15.3	23.5				
Ref. 78	*a*	2.101	2.090	2.069				
	b	0.728	0.721	0.680				
	r	349–540	429–580	485–633				

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

KCl–LiCl**	p	0	28.2	42.6	55.8	72.2	87.6	100
Ref. 52, 12	a	1.766	1.835	1.856	1.885	1.923	1.968	1.977
	b	0.433	0.489	0.507	0.528	0.561	0.509	0.583
	r	620–780	530–750	460–600	390–590	590–750	690–850	780–940
$KCl–MgCl_2$	p	10.7	20.4	31.2	41.5	49.7	59.0	80
Ref. 35, 69, 11	a	1.896	1.993	1.990	1.924	1.946	1.944	1.946
	b	0.31	0.41	0.48	0.44	0.50	0.52	0.54
	r	706–886	695–890	756–901	734–894	707–880	707–881	704–876
$KCl–MnCl_2$	p	12.6	23.2	32.1	36.6	41.3	51.0	63.5
Ref. 79	d_{500}	—	2.210	2.111	2.063	2.009	1.943	—
	d_{600}	2.337	2.157	2.051	2.007	1.955	1.881	1.795
	d_{700}	2.274	2.104	1.998	1.958	1.900	1.818	1.727
	d_{800}	2.212	2.051	1.941	1.898	1.845	1.755	1.668
KCl–NaBr	p	41.8	100					
Ref. 41	a	2.449	1.986					
	b	0.728	0.582					
	r	750–800	770–800					
KCl–NaCl**	p	0	18.7	31.1	40.6	54.8	64.8	82.9
Ref. 52, 17, 8	a	1.991	1.989	1.985	1.982	1.976	1.977	1.979
	b	0.543	0.554	0.560	0.557	0.568	0.575	0.581
	r	800–1030	780–920	710–920	710–930	670–910	680–910	720–930
KCl–NaI	p	0	8.0	19.8	33.0	49.7	73.6	100
Ref. 41	a	3.412	3.118	2.971	2.724	2.482	2.195	1.986
	b	1.00	0.824	0.900	0.815	0.727	0.625	0.582
	r	670–800	600–800	520–800	540–800	570–800	690–800	770–800
$KCl–PbCl_2$	p	0	5.51	13.21	22.94	100		
Ref. 25, 7	a	5.702	5.145	4.513	3.960	1.988		
	b	1.50	1.42	1.28	1.13	0.60		
	r	516–700	565–700	580–680	490–680	above 750		
$KCl–ZnCl_2$	p	5.4	9.3	20.0	31.1	49.2	55.9	70.1
Ref. 59	a	2.653	2.588	2.542	2.448	2.272	2.217	2.080
	b	0.55	0.50	0.62	0.66	0.60	0.60	0.57
	r	460–670	450–660	450–660	450–640	440–660	450–650	690–720
$KCl–ZnSO_4$	p	23.2	29.0	31.4	38.2	47.0	54.3	56.1
Ref. 42, 34	a	3.024	2.884	2.821	2.681	2.619	2.511	2.491
	b	0.68	0.64	0.58	0.56	0.72	0.70	0.70
	r				475–550			
KF–LiF–NaF	p_{KF}	59.0						
eutectic	p_{LiF}	29.2						
Ref. 80	a	2.47						
	b	0.68						
	r	600–800						
KI–NaCl	p	33.6	55.0	74.1	86.9	94.2	100	
Ref. 41	a	2.253	2.484	2.727	2.893	3.034	3.108	
	b	0.632	0.706	0.819	0.858	0.965	0.960	
	r	720–800	680–800	560–800	580–800	640–800	680–800	
$K_2MoO_4–MoO_3$	p	17.5	27.5	43.0	52.2	60.0	79.4	91.0
Ref. 81	a	3.9974	3.9371	3.7813	3.6534	3.4282	3.1637	3.0360
	b	1.1337	1.0997	1.1189	1.0529	0.9951	0.7146	0.6340
	r	761–869	614–750	637–792	632–779	574–766	783–933	882–978

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

KNO_2–KNO_3	*p*	0	26.5	35.9	50.7	100		
Ref. 48, 72	*a*	2.116	2.068	2.062	2.052	2.005		
	b	0.73	0.69	0.70	0.70	0.70		
	r	340–500	340–500	340–500	380–500	440–500		
KNO_2–$NaNO_2$	*p*	0	17.8	29.1	45.1	55.2	74.2	100
Ref. 48	*a*	2.004	1.959	1.951	1.961	1.951	1.963	2.005
	b	0.69	0.59	0.58	0.59	0.58	0.61	0.70
	r	380–500	260–500	260–500	260–500	350–500	350–500	440–500
KNO_2–$NaNO_3$	*p*	0	15	35	50	65	85	100
Ref. 48	*a*	2.121	2.117	2.073	2.057	2.028	1.993	2.005
	b	0.68	0.70	0.66	0.68	0.66	0.63	0.70
	r	350–500	300–500	200–500	200–500	240–500	350–500	440–500
KNO_3–$LiNO_3$	*p*	16.7	26.7	40.9	59.5	71.0	81.9	92.2
Ref. 78, 82	*a*	1.954	1.974	1.997	2.033	2.055	2.083	2.102
	b	0.599	0.623	0.638	0.683	0.696	0.729	0.735
	r	257–403	264–350	219–445	328–476	306–454	294–425	318–452
KNO_3–$NaNO_2$	*p*	0	20.5	44.0	59.4	73.1	89.3	100
Ref. 48	*a*	2.004	1.991	2.028	2.048	2.061	2.100	2.116
	b	0.69	0.61	0.66	0.67	0.67	0.72	0.73
	r	380–500	300–500	200–500	200–500	200–500	240–500	340–500
KNO_3–$NaNO_3$**	*p*	0	20	40	60	80	100	
Ref. 48, 47, 36,	*a*	2.121	2.127	2.127	2.126	2.126	2.116	
82, 8, 3	*b*	0.68	0.71	0.72	0.73	0.72	0.73	
	r	350–500	290–500	250–500	240–500	290–500	350–500	
KNO_3–NH_4NO_3	*p*	0	2.5	5.0	7.5	10.0		
Ref. 58	d_{170}	1.432	1.441	1.451	1.462	1.473		
	d_{190}	1.420	1.429	1.439	1.450	1.460		
KNO_3–$Pb(NO_3)_2$	*p*	40	50	60	70	80	90	100
Ref. 36	*a*	3.080	2.881	2.679	2.483	2.362	2.218	2.113
	b	1.00	1.00	0.908	0.750	0.787	0.709	0.730
	r	275–345	230–365	275–380	300–390	320–405	330–420	350–460
KNO_3–$Sr(NO_3)_2$	*p*	52.9	60	70	80	90	100	
Ref. 73, 36	*a*	2.403	2.360	2.285	2.226	2.167	2.113	
	b	0.721	0.760	0.748	0.752	0.753	0.730	
	r	421–452	365–445	300–420	305–465	325–475	350–460	
K_2O–SiO_2	*p*	23.9	26.7	29.9	32.9	38.7	43.6	
Ref. 56, 39	*a*	2.353	2.320	2.377	2.380	2.464	2.504	
	b	0.14	0.11	0.16	0.16	0.23	0.27	
	r			1 000–1 400				
K_2SO_4–$ZnSO_4$	*p*	26.59	32.66	35.15	36.77	41.41	49.92	58.86
Ref. 34	d_{500}	(2.841)	2.751	2.731	2.728	2.680	2.592	2.509
	d_{550}	2.812	2.727	2.708	2.692	2.641	2.556	2.485
K_2WO_4–WO_3	*p*	37.4	50.5	58.3	67.4	76.6	85.0	92.2
Ref. 83	*a*	5.889 8	5.486 5	5.332 6	4.955 3	4.532 2	4.244 4	4.077 1
	b	1.553 8	1.519 6	1.562 0	1.334 1	1.015 7	0.907 4	0.845 2
	r	897–999	772–943	655–783	682–851	803–910	860–987	904–1 029
LiCl–$LiNO_3$	*p*	6.4	13.3	20.8				
Ref. 78	*a*	1.911	1.903	1.899				
	b	0.537	0.538	0.524				
	r	278–446	340–497	378–497				
$LiClO_4$ in	p_{LiClO_4}	5	10	15				
KNO_3–$NaNO_3$	*a*	2.120 1	2.127 5	2.139 4				
eutectic	*b*	0.711 0	0.723 2	0.744 1				
(57.3% KNO_3)	*r*	—	230–400	—				
Ref. 84								

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$LiClO_4$–$LiNO_3$	*p*	34.0	57.3	82.3				
Ref. 73	*a*	2.014	2.088	2.134				
	b	0.610	0.629	0.629				
	r	240–357	198–347	225–336				
Li_2MoO_4–MoO_3	*p*	19.5	33.9	51.5	60.5	71.3	85.2	91.0
Ref. 81	*a*	3.993 2	3.895 1	3.735 9	3.564 1	2.985 6	3.455 9	3.352 0
	b	0.950 2	0.845 1	0.772 3	0.644 8	0.031 7	0.593 0	0.531 7
	r	766–921	755–924	760–934	802–962	799–950	781–905	825–924
$LiNO_3$–NH_4NO_3	*p*	0	5					
Ref. 58	d_{180}	1.426	1.430					
Li_2O–SiO_2	*p*	16.1	21.8	25.9	31.9	42.8	48.1	
Ref. 56, 39	*a*	2.311	2.355	2.359	2.344	1.980	1.955	
	b	0.13	0.19	0.20	0.22	—	—	
	r		1 100–1 400		1 250–1 400		1 400	
Li_2WO_4–WO_3	*p*	54.6	59.7	69.0	77.5	85.2	92.3	
Ref. 83	*a*	5.971 8	6.077 6	5.769 6	5.527 5	5.281 9	5.016 0	
	b	1.162 8	1.341 1	1.190 3	1.112 4	0.991 3	0.851 1	
	r	809–939	764–968	755–978	736–930	714–923	733–959	
$MgCl_2$–NaCl	*p*	20.0	45.7	60.6	75.8			
Ref. 35	*a*	1.961	1.963	2.002	2.000			
	b	0.49	0.47	0.48	0.43			
	r	750–888	732–890	722–896	712–893			
MgF_2–Na_3AlF_6	*p*	3	6	9				
Ref. 62	d_{950}	—	—	2.14				
	d_{980}	2.12	2.13	—				
MgO–SiO_2	*p*	32.8	35.5	38.3	41.1	44.0		
Ref. 74	*a*	2.547	2.579	2.597	2.655	2.670		
	b	0.049	0.056	0.052	0.071	0.070		
	r			1 600–1 950				
MoO_3–Na_2MoO_4	*p*	21.4	26.4	51.2	62.2	71.2	83.7	86.2
Ref. 51	*a*	2.79	3.63	3.92	4.02	3.88	3.74	3.81
	b	—	1.0	1.2	1.2	1.0	0.8	0.9
	r	700–830	690–790	660–760	650–810	650–750	730–840	780–880
NH_4Cl–NH_4NO_3	*p*	0	2.5	5	7.5	10		
Ref. 58	d_{170}	1.432	1.426	1.419	1.412	1.403		
	d_{180}	1.420	1.414	1.407	1.403	—		
NH_4NO_3–	*p*	92.5	95.0	97.5	100			
$(NH_4)_2SO_4$	p_{180}	—	1.435	1.430	1.427			
Ref. 58	d_{200}	1.425	1.421	1.417	1.416			
NH_4NO_3–	*p*	89.9	95.0	100				
$Pb(NO_3)_2$	d_{170}	—	1.481	1.432				
Ref. 58	d_{180}	1.527	1.475	1.426				
NH_4NO_3–	*p*	95	100					
$Sr(NO_3)_2$	d_{170}	1.466	1.432					
Ref. 58	d_{190}	1.453	1.420					
NaCl–NH_4NO_3	*p*	0	1.5					
Ref. 58	d_{180}	1.426	1.432					
NaCl–$NaNO_3$	*p*	1.4	2.8	4.2	5.7	7.1	8.6	10.1
Ref. 71	d_{350}	1.879	1.878	1.879	1.875	1.875	—	—
	d_{400}	1.842	1.841	1.843	1.839	1.839	1.840	1.836
	d_{450}	1.806	1.804	1.806	1.802	1.803	1.803	1.800

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS– *continued*

$NaCl–PbCl_2$	p	0	2.69	5.85	9.42	13.32	17.5	
Ref. 17	d_{500}	4.96	4.72	4.34	4.21	3.96	3.66	
	d_{600}	4.82	4.57	4.22	4.08	3.77	3.50	
$NaF–Na_3AlF_6$†	p	0	10	20	40	60	80	100
Ref. 38, 31, 24, 22, 15, 14, 13, 10, 9, 6	d_{1000}	2.096	2.110	2.108	2.085	2.042	1.998	1.957
	d_{1100}	2.002	2.017	2.019	2.002	1.970	1.933	1.895
$NaF–UF_4–ZrF_4$	P_{NaF}	19.0						
Ref. 85	P_{UF_4}	11.4						
	a	3.93						
	b	0.93						
	r	600–800						
$NaF–ZrF_4$	p	17.05	22.0	27.3	31.8	51.1		
Ref. 86	a	3.83	3.71	3.61	3.52	3.23		
	b	0.91	0.89	0.87	0.86	0.81		
	r			300–800				
$NaNO_2–NaNO_3$	p	0	21.3	44.8	65.4	82.1	100	
Ref. 48, 41	a	2.121	2.094	2.066	2.043	2.028	2.004	
	b	0.68	0.68	0.68	0.68	0.70	0.69	
	r	310–500	250–500	220–500	270–500	270–500	280–500	
$NaNO_3–NH_4NO_3$	p	0	2.5	5.0				
Ref. 58	d_{170}	1.432	1.443	1.452				
	d_{180}	1.426	1.436	1.446				
$NaNO_3–Pb(NO_3)_2$	p	40	50	60	70	80	90	100
Ref. 36	a	3.171	2.867	2.703	2.498	2.373	2.238	2.117
	b	1.12	0.806	0.856	0.726	0.746	0.695	0.670
	r	340–365	305–375	285–390	295–400	305–420	310–430	320–460
$Na_2O–P_2O_5$	$d_{p,t} = 2.372 + 0.204p/(100-p) - 0.338 \times 10^{-3}t$							
Ref. 87	r_p	30.4–48.5						
	r_t	liquidus–1 070						
$Na_2O–SiO_2$	p	20.0	30.8	33.6	36.9	50.0		
Ref. 56, 39	a	2.312	2.380	2.436	2.456	2.516		
	b	0.10	0.14	0.18	0.20	0.26		
	r	1 100–1 400		900–1 400		1 050–1 400		
$Na_2WO_4–WO_3$	p	45.9	50.9	55.9	65.1	74.2	83.0	91.6
Ref. 83	a	5.963 6	5.711 3	5.882 5	4.415 9	5.232 5	4.997 6	3.934 4
	b	1.424 4	1.228 9	1.557 0	–0.031 2	1.226 2	1.116 7	–0.051 0
	r	782–926	775–898	758–899	737–882	688–880	654–815	685–880
$Nd(NO_3)_2$ in $KNO_3–NaNO_3$ eutectic (57.3% KNO_3)	$P_{Nd(NO_3)_3}$	1.3	6.4	12.0	21.4	29.1	35.3	
	a	2.128 5	2.158 7	2.218 6	2.274 1	2.337 1	2.418 3	
	b	0.731 7	0.725 4	0.757 1	0.686 7	0.708 7	0.753 3	
	r				230–400			
Ref. 84								
$Nd(NO_3)_2$ in $KNO_3–LiClO_4–NaNO_3$ (45%–10%–45%)	$P_{Nd(NO_3)_3}$	35.3						
	a	2.412 8						
	b	0.707 1						
	r	230–400						
Ref. 84								
$PbBr_2–PbCl_2$	p	0	24.46	57.19	87.88	100		
Ref. 25, 2	a	5.702	5.840	6.025	5.264	6.338		
	b	1.50	1.52	1.55	1.71	1.65		
	r	516–570	492–620	465–640	410–600	505–600		
$PbCl_2–ZnCl_2$	p	67.1						
Ref. 89	d_{510}	3.733						
	d_{553}	3.703						

Table 9.2 DENSITIES OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$PbO-B_2O_3$	p	57.9	68.1	76.3	82.9	88.2	92.9	96.6
Ref. **88**	d_{1050}	2.8	3.5	4.0	4.6	5.3	6.0	6.6
$PbO-SiO_2$	p	61.4	71.2	78.8	84.8	89.7	93.7	97.1
Ref. **88**	d_{1050}	4.2	4.9	5.7	6.0	6.7	7.0	7.4
$PbO-V_2O_5$	p	15.3	39.6	52.8	65.4	79.0	85.1	92.1
Ref. **90**	d_{1000}	3.1	4.0	5.0	5.0	6.2	6.8	7.8
$PbO-SiO_2-V_2O_5$	P_{PbO}	28.5	38.6	58.4	60.0	68.5	80.0	
Ref. **90**	P_{SiO_2}	10.3	10.4	10.4	10.1	10.6	10.0	
	d_{1000}	3.8	3.8	4.0	4.0	4.0	5.2	
$SrO-SiO_2$	p	48.1	53.4	58.5	63.3	67.8		
Ref. 74	a	3.129	3.247	3.384	3.493	3.612		
	b	0.058	0.059	0.074	0.079	0.072		
	r			1600–1950				
$TlCl-ZnSO_4$	p	55.23	57.99	59.86	61.04	63.55	69.24	74.82
Ref. **34**	d_{450}	(4.116)	4.146	4.196	4.223	4.277	4.421	(4.573)
	d_{500}	4.076	4.094	4.155	4.177	4.227	4.376	4.512

* See also $NaF-Na_3AlF_6$.
† See also $AlF_3-Na_3AlF_6$
** See also 'Physical Properties Data Compilations Relevant to Energy Storage II Molten Salts—Data on Single and Multi-Component Salt Systems', Janz *et al.*, NSRDS–NBS 61.

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Table 9.3 DENSITY OF SOME SOLID INORGANIC COMPOUNDS AT ROOM TEMPERATURE

Compound	*Density* g cm^{-3}	*Compound*	*Density* g cm^{-3}	*Compound*	*Density* g cm^{-3}	*Compound*	*Density* g cm^{-3}
AgBr	6.47	CsI	4.51	$LaCl_3$	3.84	Rb_2SO_4	3.61
AgCl	5.56	$CsNO_3$	3.69	LiBr	3.46	ReF_6	4.25
$AgClO_3$	4.43	Cs_2SO_4	4.24			Re_2O_7	6.10
AgI(α)	5.683			LiCl	2.07	$ReOF_4$	4.03
$AgNO_2$	4.35	Cu_2Cl_2	4.14	Li_2CO_3	2.11	$SbBr_3$	4.15
		Cu_2O	6.0	LiF	2.64		
$AlBr_3$	2.64	$GaBr_3$	3.69	$LiNO_3$	2.38	$SbCl_3$	3.14
$AlCl_3$	2.44	$GaCl_3$	2.47	Li_2SO_4	2.22	$SnCl_2$	3.95
AlI_3	3.98	GaI_3	4.15			SnI_4	4.47
$AsBr_3$	3.54			$MgCl_2$	2.32	$SrBr_2$	4.22
BI_3	3.35	H_3BO_3	1.44	MgF_2	3.0	$SrCl_2$	3.05
		$HgBr_2$	6.11	MgO	3.58		
B_2O_3	1.84	Hg_2Br_2	7.31	MnO_2	4.9	SrF_2	4.24
$BaBr_2$	4.78	$HgCl_2$	5.44	Na_3AlF_6	2.90	SrI_2	4.55
$BaCl_2$	3.856	Hg_2Cl_2	7.15			SrO	4.7
$BaCO_3$	4.43			$Na_2B_4O_7$	2.37	$TeCl_4$	3.26
BaF_2	4.89	HgF_2	8.95	NaBr	3.20	$ThCl_4$	4.59
		HgI_2	6.36	NaCl	2.17		
BaI_2	5.15	Hg_2I_2	7.7	Na_2CO_3	2.53	$TiBr_4$	2.6
BaO	5.68	$InBr_3$	4.74	NaF	2.56	TiF_4	2.80
BaO_2	4.96	InCl	4.19			TiI_4	4.3
$BaSO_4$	4.50			NaI	3.67	TiO_2	4.26
$BeBr_2$	3.47	$InCl_2$	3.66	$NaNO_3$	2.26		rutile
		$InCl_3$	3.46	NaOH	2.13		3.84
$BeCl_2$	1.90	InI_3	4.69	$Na_4P_2O_7$	2.53		anatase
BeF_2	1.99	KBF_4	2.55	Na_2SO_4	2.70	TlBr	7.56
BeO	3.00	KBr	2.75				
$BiBr_3$	4.72			Na_2WO_4	4.18	TlCl	7.00
$BiCl_3$	4.75	KCl	1.98	NH_4Cl	1.53	TlI	7.1
		KCN	1.52	$Ni(CO)_4$†	1.32	$TlNO_3$	5.8
C_2Cl_6	2.09	K_2CO_3	2.43	NiO	6.67	WCl_5	3.88
$CaBr_2$	3.353	$K_2Cr_2O_7$	2.68	OsO_4	4.91	WCl_6	3.52
$CaCl_2$	2.15	KF	2.48				
$CaCO_3$	2.71*			PBr_3	2.85	WO_3	7.2
CaF_2	3.18	$KHSO_4$	2.31	$PbBr_2$	6.66	UCl_4	4.87
		KI	3.13	$PbCl_2$	5.85	YCl_3	2.8
CaO	3.25/3.38	$KMnO_4$	2.91	$PbCl_4$†	3.18	$ZnBr_2$	4.20
$CaSO_4$	2.96	KNO_3	2.11	PbI_2	6.16	$ZnCl_2$	2.91
$CdBr_2$	5.19	KOH	2.04				
$CdCl_2$	4.05			RbBr	3.35	ZnI_2	4.74
CsBr	4.43	K_3PO_4	2.56	RbCl	2.80		
		K_2SiF_6	3.08 (hex)	RbF	3.56		
CsCl	3.99		2.67 (cub)	RbI	3.55		
CsF	4.12	K_2SO_4	2.66	$RbNO_3$	3.11		

* Calcite. † Liquid.

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Table 9.4 ELECTRICAL CONDUCTIVITY OF PURE MOLTEN SALTS

The conductivity in Ω^{-1} cm^{-1} is given at the melting point θ_m, and at 50° intervals beginning at θ, or as an equation in the temperature t, or at the temperatures given in brackets. All temperatures are in °C. Extrapolated conductivities are also bracketed. Principal references are in **bold type**.

			Conductivity Ω^{-1} cm^{-1}							
Substance	θ_m °C	θ °C	θ_m	θ	$\theta+50$	$\theta+100$	$\theta+150$	$\theta+200$	$\theta+250$	*References*
AgBr	430	450	2.8561	2.903	3.016	3.119	3.214	3.3	3.378	**133, 96, 19, 18,** 22
AgCl	455	500	3.817	3.972	4.131	4.276	4.407	4.523	4.626	**133, 96, 76, 19, 18,** 107, 22
$AgClO_3$	231	250	0.417	0.474	—	—	—	—	—	**13**
AgI	557	600	2.3	2.35	2.40	2.45	2.5	2.55	—	**19, 12**
$AgNO_3$	210	250	0.67	0.84	1.05	1.24	—	—	—	**106, 100, 88, 87, 86, 85, 79, 76, 55,** 71, 22, 13, 4
$AlBr_3$	97	150	$(<10^{-8})$	(0.02×10^{-6})	0.10×10^{-6}	0.19×10^{-6}	(0.26×10^{-6})	—	—	**27,** 70, 68, 66, 62
$AlCl_3$	193	200	4.6×10^{-7}	5.5×10^{-7}	11.1×10^{-7}	—	—	—	—	37, 60, 53, 52, 40
AlI_3	191	200	(1.205×10^{-6})	1.852×10^{-6}	5.645×10^{-6}	7.1×10^{-6}	—	—	—	**36, 37**
$AsBr_3$	31	35	—	2.6×10^{-7}	—	—	—	—	—	**59,** 7
$AsCl_3$	−16	—	1.0×10^{-7}	—	—	—	—	—	—	**39, 6,** 38
AsF_3	−13	0	1.56×10^{-5}	1.84×10^{-5}	2.92×10^{-5}	—	—	—	—	**74**
AsI_3	142					Poor				**8**
BCl_3	−107					Non-conductor				**6**
BF_3	−128.7	−120	—	$<5.0\times10^{-10}$	—	—	—	—	—	74
B_2O_3	570	600	—	1.2×10^{-6}	3.0×10^{-6}	5.2×10^{-6}	1.5×10^{-5}	2.3×10^{-5}	3.6×10^{-5}	101, 99, 81, 12, 10
		900	—	6.6×10^{-5}	9.7×10^{-5}	1.5×10^{-4}	2.1×10^{-4}	2.9×10^{-4}	4.0×10^{-4}	
		1 200	—	5.3×10^{-4}	—	—	—	—	—	
$BaBr_2$	847	850	—	1.178	1.307	1.440	1.572	1.705	—	**108**
$BaCl_2$	960	975	—	2.085		2.176 (1 000) 2.472 (1 075)	2.264 (1 025) 2.532 (1 100)	2.354 (1 050)		**108,** 109, 107, 105, 78, 64, 56, 9
BaI_2	711	750	—	0.784	0.910	1.024	1.136	1.248	1.361	**108**
$Ba(NO_2)_2$	—	280	—	0.182		0.235(300)	0.260(310)			**110**
$BeCl_2$	405	450	0.87×10^{-3}	2.986×10^{-3}	0.016	—	—	—	—	**111**

BeF_2	*c.* 800					Poor				**34**
BeI_2	510					Non-conductor				**5**
$BiBr_3$	—	250	—	0.3214	0.3813	0.4237	0.4487	0.4562	0.4462	**111**
		550	—	0.320	0.298	0.260	0.224	—	—	
$BiCl_3$	230	250	—	0.4122	0.4910	0.546	0.5772	0.5845	0.5680	**134**, 32
	550	—	—	0.515	0.468	—	—	—	—	
BiI_3	—	400	—	0.285	0.300	0.310	0.309	0.305	0.295	**111**
		700	—	0.285	0.265	0.250	0.227	0.205	—	
$Bi_2(MoO_4)_3$	—	708	—	0.274		0.333(747)	0.433(794) 0.480(817) 0.550(847)			**112**
$CaBr_2$	—	750	—	1.420	1.573	1.727	1.882	2.037	2.194	**108**
$CaCl_2$	—	800	—	2.116	2.342	2.515	2.778	3.006	—	**108**, 105, 104, 78, 64, 63, 57, 56, 46, 42, 36, 22, 14, 12, 9, 107, 109
CaF_2	1420	1500	—	3.9	4.1	—	—	—	—	**90**
CaI_2		800	—	1.172	1.292	1.390	1.486	1.566	—	**108**
$CdBr_2$	565	600	—	1.125	1.229	1.324	1.419	1.517	—	**108**, 65
$CdCl_2$	568	600	—	1.950	2.085	2.206	2.317	2.425	—	**108**, 91, 86, 82, 65, 31, 22
CdI_2	390	400	—	0.210	0.316	0.425	0.533	0.640	0.750	**108**, 82
$CeCl_3$	—	828	—	1.12		1.17(844)	1.21(858) 1.23(868) 1.29(886) 1.30(895) 1.38(931)			**113**
CeI_3	761	796	—	0.448		0.470(814)	0.499(836) 0.523(860)			**114**
CsBr	635	650	—	0.84	0.97	1.09	1.21	1.31	—	**98**
CsCl	645	650	—	1.12	1.27	1.42	1.57	1.71	1.83	**98**, 31, 115
CsF	—	—		$\kappa_t = -4.511 + 1.642 \times 10^{-2} t - 7.632 \times 10^{-6} t^2$ at 725–921						**109**
CsI	630	650	—	0.69	0.80	0.91	1.00	1.09	—	**98**
$CsNO_3$	417	—		$\kappa_t = -0.2452 + 1.8878_5 \times 10^{-3} t$ at 415–491						**116**, 21
CuCl	430	450	3.26	3.32	3.46	3.56	3.66	—	—	**86**, 31
Cu_2S	1130	1150	60	70	80	90	100	120	130	**97**, 16
		1450	—	140	160	—	—	—	—	
$ErCl_3$	—	801	—	0.468		0.496(818)	0.531(839)			**117**
FeS	1200	1250	1560	1540	1530	1520	1510	1500	1490	**97**
$GaBr_2$	—	—		$\log \kappa_t = 1.142 - 865/(t + 273)$ at 167–189						**118**
$GaBr_3$	125	—	5.0×10^{-8}	—	—	—	—	—	—	**41**
$GaCl_2$	—	—		$\log \kappa_t = 1.180 - 784/(t + 273)$ at 167–176						**118**, 2
$GaCl_3$	77	—	10^{-8} (approx.)	—	—	—	—	—	—	**41**

Table 9.4 ELECTRICAL CONDUCTIVITY OF PURE MOLTEN SALTS—*continued*

Substance	θ_m °C	θ °C	Conductivity Ω^{-1} cm^{-1}							References
			θ_m	θ	$\theta+50$	$\theta+100$	$\theta+150$	$\theta+200$	$\theta+250$	
Ga_2I_4	—	—			$\log \kappa_t = 2.887 - 1\,401/(t+273)$ at 150–211 $\log \kappa_t = 1.292 - 1\,114/(t+273)$ at 211–279 $\log \kappa_t = 0.460 - 653.4(t+273)$ at 279–350					**119**
Ga_2I_6	—	—			$\log \kappa_t = -0.068 - 1\,041/(t+273)$ at 185–222 $\log \kappa_t = -1.807 - 624.4/(t+273)$ at 222–284 $\log \kappa_t = -2.660 - 147.6/(t+273)$ at 284–352 $\log \kappa_t = -4.211\ 2 + 822.6/(t+273)$ at 352–400					**119**, 41
$GdBr_3$	—	800	—	0.444			0.476(823) 0.500 (842)			**117**
$GdCl_3$	—	629	—	0.382			0.408(649) 0.465(675) 0.506(698)			**117**
$HgBr_2$	235	240	—	1.38×10^{-4}			2.08×10^{-4}(280) 2.85×10^{-4}(320)			**108**, 120, 75, 23
$HgCl_2$	277	280	—	3.20×10^{-5}			3.57×10^{-5}(290) 3.96×10^{-5}(300)			**108**, 120, 55, 23
Hg_2Cl_2	525	550	1.00	1.03	—	—	—	—	—	**36**
HgI_2	250	260	—	0.029 9	0.024 0			0.018 8(350)		**108**, 120, 83, 55, 23
$HoCl_3$	—	747	—	0.431			0.488(776) 0.526(800) 0.562(819)			**117**
$InBr_3$	436	450	0.168	0.167	0.162	0.156	—	—	—	**37**
InCl	225	250	0.88	1.04	1.33	1.62	(1.89)	—	—	**37**
$InCl_2$	235	250	0.23	0.26	0.36	0.46	0.56	0.64	0.72	**37**
$InCl_3$	498	500	(0.50)	(0.50)	(0.46)	0.41	0.37	0.32	(0.28)	**37**
InI_3	210	250	0.052	0.066	0.080	0.092	(0.100)	—	—	**37**
K_3AlF_6	1 035	1 050	2.33	2.38	—	—	—	—	—	**102**
KBF_4	—	550	—	1.075	1.180	1.243	—	—	—	**121**
KBr	742	—			$\kappa_t = -1.327_1 + 5.710_0 \times 10^{-3} t - 2.313_9 \times 10^{-6} t^2$ at 760–980					**122**, 98, 82, 31, 21, 70, 12, 4
KCl	770	800	2.12	2.22	2.35	2.46	2.56	2.65	2.73	**92**, **82**, **78**, **77**, **63**, **44**,
		1 100	—	2.79	—	—	—	—	—	107, 68, 56, 54, 49, 37, 22
$KClO_3$	368	—	4.19	—	—	—	—	—	—	**1**
K_2CO_3	895	900	2.020	2.035	2.178 3	2.322 1	—	—	—	**135**
$K_2Cr_2O_7$	398	400	0.200	0.204	0.298	0.389	(0.474)	—	—	**83**, **11**
KF	857	900	—	4.4728	4.601 7	4.697 5	4.760 3	—	—	**109**, 121, 102, 47, 42, 29, 21
					$\kappa_t = -3.493 + 1.480 \times 10^{-2} t - 6.608 \times 10^{-6} t^2$ at 869–1 040					

$KHSO_4$	212	301	0.049	0.141	--	—	—	—	—	**72**
KI	682	700	1.82	1.32	1.42	1.52	1.60	1.66	—	**92, 82, 31,** 21, 12, 4
K_2MoO_4	—	—			$\kappa_t = -21.021\,0 + 4.482\,3 \times 10^{-2} t - 22.506\,6 \times 10^{-6} t^2$ at 931–988					**123**
KNH_2	330	340	—	0.389	—	—	—	—	—	**20**
KNO_3	337	350	0.62	0.66	0.82	0.96	1.10	1.24	1.38	**106, 93, 87, 86, 84, 83, 82, 61, 55, 22, 21,** 116, 15, 11, 1
KOH	410				*See* ref.					35
K_2SO_4	1 069	1 100	(1.78)	1.84	1.94	---	- -	—	—	**9**
K_2TaF_7	—	750	—	0.750	0.919	0.981	(1.052)	---	—	**121**
K_2TiF_6	—	850	—	1.359	1.462	1.559	(1.650)	- -	—	**121,** 124
K_2WO_4	—	—			$\kappa_t = -8.295\,3 + 1.763\,3 \times 10^{-2} t - 8.029\,5 \times 10^{-6} t^2$ at 946–1 024					**125**
$LaCl_3$	885	900	1.550	1.602	1.748	1.853 1	1.917 0	—	—	**36, 109**
Li_3AlF_6	—	800	—	3.45	3.65	3.80	3.95	--	—	**102**
LiBr	550	600	4.69	4.97	5.23	5.49	5.73	—	—	**98,** 65
LiCl	614	650	5.730 6	5.921 9	6.171 4	6.402 1	6.613 9	6.807	6.981 3	**92, 82, 77, 49, 31, 107,** 60, 42
$LiClO_3$	—	131.8	—	0.115 1		0.123 1(135.7) 0.137 0(140.8)	0.125 8 (136.5) 0.142 0(143.0)			**126**
LiF	844	875	- -	8.663		8.889(915) 9.058(958) 9.306(1 037)	9.216 (1 008)			**121,** 109, 102, 42
LiI	465	500	—	3.800	4.067	4.250	4.417	4.570	4.703	**127,** 98
		800	- -	4.830	4.947	5.045	---	----	—	
Li_2MoO_4	—	—			$\kappa t = 43.259\,6 - 10.71 \times 10^{-2} t + 72.668 \times 10^{-6} t^2$ at 790–939					**123**
$LiNO_3$	254	300	0.803 8	1.054 5	1.335 7	1.625 9	1.925 1	2.233 3	—	**138,** 13, 21
Li_2WO_4	--	—			$\kappa_t = -7.506\,7 + 1.873\,3 \times 10^{-2} t - 8.803\,4 \times 10^{-6} t^2$ at 762–903					**125**
$MgBr_2$	—	750	—	0.766	0.857	0.950	1.045	1.138	—	**108**
$MgCl_2$	714	750	1.014	1.085	1.183	1.283	1.383	1.483	—	**108,** 91, 78, 63, 54, 48, 44, 31
MgI_2	—	650	—	0.408	0.496	0.585	0.675	0.765	0.856	**108**
$MnCl_2$	—	850	—	(1.436)	1.578	1.690	—	----	---	**107,** 128
$MoCl_5$	194	200	—	0.3×10^{-6}	6.3×10^{-6}	---	---	—	—	**32**
MoO_3	795	—			$\kappa_t = -5.753\,7 + 1.456\,3 \times 10^{-2} t - 8.194\,9 \times 10^{-6} t^2$ at 823–891					**123,** 89
Na_3AlF_6	1000	1040	2.799	2.901	2.997	—	—	—	----	**102, 80,** 77, 73, 69, 51, 50, 29
NaBr	745	800	2.87	3.06	3.22	3.37	3.49	-	—	**98,** 12, 4

Table 9.4 ELECTRICAL CONDUCTIVITY OF PURE MOLTEN SALTS—*continued*

Substance	θ_m °C	θ °C	*Conductivity* $\Omega^{-1}\,cm^{-1}$							*References*
			θ_m	θ	$\theta+50$	$\theta+100$	$\theta+150$	$\theta+200$	$\theta+250$	
NaCl	800	850	3.58	3.74	3.87	4.02	4.16	4.29	4.39	**104, 92, 78, 77, 63, 107‡**
NaCN	562	700	—	1.15	1.27	1.39	—	—	—	**42**
Na_2CO_3	850	900	2.834 7	3.029	3.222	—	—	—	—	**135**
NaF	992	1 003	—	4.960		4.985(1 018) 5.082(1 047) 5.111(1 059) 5.179(1 086) 5.209(1 099) 5.271(1 122) 5.335(1 138)				**121**, 102, 80, 50, 29
$NaHSO_4$	182	200	0.067	0.094	0.168	0.241	—	—	—	**72**
NaI	655	700	2.30	2.41	2.55	2.68	2.80	2.92	—	**98, 82, 12,** 4
Na_2MoO_4	687	750	(1.15)	1.26	1.37	1.49	1.57	1.66	1.74	**89, 21**
		1 050	–	1.82	1.90	1.98	2.07	2.14	2.22	
		1 350	–	2.30	2.37	—	—	—	—	
$NaNH_2$	208	210	—	0.593	–	—	—	—	—	**20**
$NaNO_2$	270	300	—	1.34	1.62	1.89	2.16	—	—	**91, 82**
$NaNO_3$	310	350	0.94	1.16	1.36	1.55	1.73	—	—	**95, 93, 86, 82, 79, 55, 21, 22, 11**
NaOH	322	350	2.125	2.377	2.827	3.277	—	—	—	**35**
$NaPO_3$	625	650	0.36	0.425	0.55	0.675	0.80	0.925	1.05	**12**
		950		1.175	1.30	1.42	1.54			
Na_2SO_4	885	900	(2.19)	2.23	2.37	2.50	2.64	2.77	(2.91)	**9**
Na_2TaF_7	—	750	—	0.750	0.919	0.981	(1.052)	—	—	**121**
Na_2WO_4	696	—		$\kappa_t = -1.4108 + 0.3451 \times 10^{-2} t - 0.2058 \times 10^{-6} t^2$ at 706–871						**125,** 21
$NbCl_5$	210	228	—	0.22×10^{-6}	—	—	—	—	—	**26**
$NdBr_3$	—	713	—	0.466			0.498(731) 0.519(743) 0.541(759) 0.563(772) 0.603(797)			**117**
$NdCl_3$	761	800	(0.587)	0.692	0.821.	0.945	(1.058)	—	—	**32**
NdI_3	787	799	—	0.396			0.416(818) 0.440(842)			**114**
NH_4HSO_4	145	150	0.079	0.086	0.154		—	—	—	**72**
NH_4NO_3	169.6	200	0.31	0.41	(0.53)	—	—	—	—	**4,** 1
$PbBr_2$	370	400	(0.57)	0.68	0.85	1.03	1.19	—	—	**96, 11,** 22
$PbCl_2$	498	500	5.829 5	5.839 8	6.088	6.316 6				**136, 137, 96, 107, 11**
$PbCl_4$	−15	0	—	8.0×10^{-7}	—	—	—	—	—	**32**
PbI_2	—	450	–	0.432 6	0.462 8	0.493 9	0.530 6	0.390 6(402.7)		**127**
$PbMoO_4$	—	1 098	–	0.938		0.950(1 107)	0.958(1 116)	0.963(1 118)		**112**
$PrBr_3$	—	727	–	0.52			0.56(750) 0.60(770)			**117**

$PrCl_3$	—	..				$\kappa_t = -1.189 + 2.75 \times 10^{-3} t$ at 800–860				**129**, 32
PrI_3	738	763	—	0.399			0.426(786) 0.452(809)			**114**
RbBr	692	700	—	1.132	1.263	1.360	1.454	1.526	1.586	**127, 98**
		1 000	—	1.637	1.679	1.716	1.749	1.778	1.806	
RbCl	722	750	1.50	1.58	1.72	1.85	1.97	—	—	**98, 31**
RbI	647	650	—	0.86	0.96	1.04	1.12	1.19	1.25	**98**
$RbNO_3$	316	350	0.431	0.509	0.618	0.72	0.8162	—	—	**21**
$SbBr_3$	97	100	228×10^{-6}	236×10^{-6}	355×10^{-6}	450×10^{-6}	—	—	—	**23**, 45
$SbCl_3$	73	—	0.5×10^{-6}	—	..	..	..	—	—	**43, 33**, 25
SbF_3	290	300	—	0.065	–	.	—	—	—	**94**
SbF_5	6	50	0.4×10^{-8}	5.85×10^{-8}		41.0×10^{-8}(80)	—	—	—	**74**
SbI_3	170	200	3.91×10^{-8}	3.91×10^{-8}	4.83×10^{-8}	5.68×10^{-8}	6.44×10^{-8}	(7.11×10^{-8})	—	**23**
$ScCl_3$	960	980	0.56	0.63		0.66 (1 000)	..	—	—	**37**, 32, 28
SiO_2	—	—			*ca.* 10^{-5}	*ca.* 10^{-4} at 1 800–2 600				**130**
$SnCl_2$	247	250	0.89	0.90	1.11	1.38	1.67	(1.93)	—	**86, 36**, 3
$SrBr_2$	—	650	—	0.728	0.980	1.142	1.295	1.446	1.600	**108**
$SrCl_2$	872	900	1.989	2.096	2.285	2.477	2.670		—	**108**, 9
SrI_2	.	550	—	0.516	0.637	0.758	0.875	0.989	1.100	**108**
		850	..	1.212	1.320	1.422	1.525	—	—	
$TaCl_5$	221	235	—	0.3×10^{-6}	—	—	—	—	—	**26**
$TeCl_2$	175	200	(0.005)	0.034	0.089	0.145	—	—	—	**32**
$TeCl_4$	224	250	0.100	0.131	0.186	–	—	—	—	**32**
$ThCl_4$	770	800	(0.54)	(0.61)	0.71		(0.86)		—	**37**
TiI_4	150					$1 \times 10^{-7} - 6 \times 10^{-7}$ (180–240)				**41**
TlBr	460	—			$\kappa_t = -0.461_1 + 3.105_0 \times 10^{-3} t - 0.732_6 \times 10^{-6} t^2$ at 480–705					**131**, 18
TlCl	430	450	1.088	1.164	1.350	1.532	1.700	(1.865)	—	**83, 17**, 22
$TlCl_3$	*c.* 60	—	$< 5.0 \times 10^{-5}$	—	—	—	—	—	—	**37**
TlI	440	450	(0.530)	0.551	0.651	0.747	0.840	—	—	**17**
$TlNO_3$	206	250	(0.35)	0.47	0.60	—	..	—	—	**84, 55**, 22
Tl_2S	448					*See* ref.				24
UCl_4	567	—				$\kappa_t = -0.318 + 1.22 \times 10^{-3} t$				**132**, 32
WCl_5	248	250	0.61×10^{-6}	0.67×10^{-6}	1.84×10^{-6}	—	—	.	—	**32**, 25
WCl_6	275	300	1.86×10^{-6}	2.60×10^{-6}	4.05×10^{-6}	(320)	6.94×10^{-6}	(330)	—	**32**, 25
YCl_3	721	750	0.42	0.48	0.58	0.69	0.79	—	—	**37**
$ZnBr_2$	—	400	—	0.020	0.043	0.085	0.145	0.215	0.310	**108**
$ZnCl_2$	331	350	—	0.007	0.020	0.050	0.090	0.156	0.243	**108**, 103, 31, 1
		650	—	0.350	0.462	—	..	—	—	
ZnI_2	—	450	—	0.060	0.118	0.190	0.267	—	–	**108**

‡ *See also* 64, 60, 58, 57, 56, 54, 53, 52, 48, 46, 42, 31, 22, 4.

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Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS

The electrical conductivity in Ω^{-1} cm^{-1} at temperature t °C and composition p(wt.%) of the first-named constituent is given as κ_t, or empirical equations for κ as a function of temperature within the stated range are given at each composition. Principal references are in **bold type**.

AgBr-AgCl	p	0	24.7	46.7	66.9	84.0	100	
Ref. **59**, **3**	κ_{450}	—	3.52	3.33	3.16	3.00	2.89	
	κ_{500}	3.90	3.70	3.50	3.31	3.16	3.02	
	κ_{550}	4.07	3.86	3.64	3.44	3.28	3.13	
	κ_{600}	4.21	3.99	3.77	3.55	3.38	3.21	
AgBr–KBr	p	52.2	61.9	78.0	90.1	100		
Ref. **59**	κ_{400}	—	—	1.42	1.98	—		
	κ_{500}	—	1.29	1.70	2.23	3.03		
	κ_{600}	1.43	1.55	1.91	2.43	3.21		
AgBr–KCl	p	38.6	62.6	79.0	91.0	100.0		
Ref. **77**, **78**	κ_{500}	—	—	1.678	2.210	3.020		
	κ_{600}	—	1.680	1.942	2.432	3.215		
	κ_{700}	1.872	1.933	2.172	2.602	3.374		
	κ_{800}	2.127	2.150	2.340	2.742	3.505		
AgCl–$AgNO_3$	p	0	9.00	12.5	15.5	20.0	30.0	40.0
Ref. **36**	κ_{220}	0.706	0.705	0.710	0.712	—	—	—
	κ_{270}	0.926	0.926	0.931	0.932	0.950	1.005	1.092
	κ_{320}	1.132	1.132	1.138	1.138	1.161	1.223	1.312
AgCl–$AlBr_3$	p				13.29			
Ref. **13**	t	100	110	125	130	140	155	170
	κ	1.07	1.21	1.61	1.68	1.90	2.67	3.22
AgCl–KBr	p	23.2	44.6	64.4	83.0	100.0		
Ref. **77**, **78**	κ_{500}	—	—	1.742	2.600	3.965		
	κ_{600}	1.400	1.570	2.008	2.871	4.277		
	κ_{700}	1.637	1.805	2.215	3.065	4.526		
	κ_{800}	1.815	1.980	2.390	3.220	4.716		
AgCl–KCl	p	50.2	63.0	72.5	87.9	100		
Ref. **59**	κ_{400}	—	—	—	2.30	—		
	κ_{500}	—	—	1.93	2.70	3.90		
	κ_{600}	—	2.01	2.24	3.00	4.21		
	κ_{700}	2.16	2.31	2.51	3.22	4.46		
AgCl–$PbCl_2$	p	0	11.2	25.6	43.5	76.3	100	
Ref. **59**	κ_{400}	—	—	1.27	1.67	2.62	—	
	κ_{500}	1.43	1.59	1.82	2.20	3.11	3.90	
	κ_{600}	1.92	2.07	2.27	2.61	3.46	4.21	
	κ_{700}	2.33	2.51	2.68	2.96	3.73	4.46	
AgCl–TlCl	p	0	20.6	37.0	58.0	77.2	100	
Ref. **3**	κ_{500}	1.215	1.470	1.711	2.260	2.925	3.653	
AgI–$AgNO_3$	p	0	10	20	30	40	50	60
Ref. **62**, **33**	κ_{150}	—	—	—	0.38	0.44	0.54	0.65
	κ_{200}	—	—	0.58	0.60	0.66	0.75	0.86
	κ_{250}	0.80	0.78	0.78	0.80	0.85	0.93	1.03
	κ_{300}	1.00	0.98	0.98	1.00	1.05	1.12	1.21
$AgNO_3$–$Cd(NO_3)_2$	p	23.5	32.3	41.7	51.8	62.6	74.1	100
Ref. **46**	κ_{150}	—	—	0.07	0.15	—	—	—
	κ_{200}	—	0.11	0.19	0.28	0.38	0.54	—
	κ_{250}	0.15	0.23	0.34	0.44	0.55	0.65	0.83
	κ_{300}	0.27	0.38	0.49	0.61	0.73	0.86	—
$AgNO_3$–HgI_2	p	4.0	13.8	27.2	35.9	46.6	59.9	77.0
Ref. **53**, **19**	κ_{100}	—	—	—	0.08	0.07	0.08	0.08
	κ_{150}	0.02	0.11	0.12	0.20	0.15	0.22	0.31
	κ_{200}	0.09	0.24	0.22	0.30	0.27	0.36	0.51

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$AgNO_3$–KNO_3	p	0	20	40	60	80	90	100
Ref. 71, 61, 51, 79	κ_{250}	—		0.47	0.54	0.66	0.74	0.84
	κ_{300}		0.56	0.64	0.73	0.85	0.93	1.05
	κ_{350}	0.66	0.73	0.81	0.91	1.04	1.13	1.24
$AgNO_3$–$LiNO_3$	p	0	38.0	62.0	78.6	90.7	100	
Ref. 61	κ_{250}	0.78	0.79	0.80	0.81	0.82	0.83	
	κ_{300}	1.05	1.04	1.04	1.04	1.04	1.04	
$AgNO_3$–$NaNO_3$	p	0	10	20	30	40	60	100
Ref. 38	κ_{290}	—	0.900	0.907	0.910	0.920	0.941	1.010
	κ_{330}	1.076	1.088	1.094	1.104	1.103	1.118	1.173
	κ_{370}	1.251	1.267	1.264	1.277	1.272	1.289	
$AgNO_3$–$RbNO_3$	p	22.3	33.0	43.4	63.3	72.9	82.2	91.2
Ref. 52	κ_{200}	—	0.24	0.28	0.37	0.43	0.49	0.57
	κ_{250}	0.33	0.38	0.42	0.54	0.61	0.69	0.77
	κ_{300}	0.47	0.52	0.58	0.71	0.78	0.87	0.96
$AgNO_3$–$TlNO_3$	p	10	35	45	50	60	65	90
Ref. 29, 3	κ_{100}	—		0.137	0.123	0.145		
	κ_{200}	0.336	0.405	0.424	0.427	0.468	0.488	0.560
	κ_{300}	0.607	0.712	0.735	0.753	0.808	0.824	0.943
$AlBr_3$ $HgBr_2$	p	59.7	60.5	63.9	68.0	79.0	89.6	92.2
Ref. 25, 3	$10^2 \cdot \kappa_{110}$	1.38	1.34	1.22	1.00	0.419	0.064	0.013
	$10^2 \cdot \kappa_{1140}$	2.45	2.34	2.00	1.61	0.573	0.064	0.013
$AlBr_3$ KBr	p	81.8	83.2	84.7	86.2	87.5	88.0	
Ref. 30, 23, 2	κ_{110}	0.036 0	0.033 1	0.030 1	0.026 9	(0.024 2)	0.023 3	
	κ_{140}	0.060 1	0.054 6	0.049 3	0.043 9	(0.039 6)	0.037 9	
$2AlBr_3 \cdot KCl$	t	90	100	140	160	170		
Ref. 28, 13	κ	0.023 2	0.029 5	0.058 7	0.074 2	0.082 9		
$4AlBr_3 \cdot LiCl$	t	80	100	120	140	170	180	
Ref. 13	κ	0.011 0	0.013 9	0.017 0	0.020 4	0.024 2	0.025 1	
$AlBr_3$–$NaBr$	p	83.8	84.7	85.6	86.8	87.9	88.9	
Ref. 30	κ_{120}	0.057 8	0.053 3	0.049 2	0.044 1	0.038 2	0.034 6	
	κ_{130}	0.067 4	0.061 3	0.056 5	0.050 6	0.044 4	0.040 2	
	κ_{140}	0.077 8	0.068 7	0.064 1	-	0.050 0	0.045 7	
$2AlBr_3 \cdot NaBr$	t	110	130	150	170			
Ref. 28	κ	0.051 5	0.069 2	0.088 7	0.108 7			
$AlBr_3$–$NaCl$	p	90.73	93.69	94.83		at $p = 80.1$, $\kappa_{170} = 0.036\,5$		
Ref. 13	κ_{110}	0.025 2	0.026 2	0.022 0				
	κ_{130}	0.041 5	0.031 0	0.025 2				
	κ_{150}	-	0.042 8	0.031 3				
$AlBr_3$–NH_4Br	p	84.50	86.90	88.98	89.42	90.81		
Ref. 25	κ_{110}	0.022	0.019	0.017	0.016	0.014		
	κ_{130}	0.033	0.027	—	0.022	0.020		
	κ_{150}	0.043	0.036	0.031	0.029	0.025		
$2AlBr_3 \cdot NH_4Br$	t	110	160					
Ref. 28	κ	0.022 0	0.048 4					
$AlBr_3$–$SbBr_3$	p	0	7.58	19.74	26.65	42.45	74.69	86.91
Ref. 23, 2	$10^3 \cdot \kappa_{100}$	0	12	18	16	11	4	1
	$10^3 \cdot \kappa_{140}$	0	16	25	26	20	7	1
$AlBr_3 \cdot SbBr_3$	t	100	150	170				
Ref. 28	$10^3 \cdot \kappa$	11.6	26.3	32.2				
$AlBr_3 \cdot SbBr_3$ $AsBr_3$	p	16.3	32.9	41.4	67.9	77.3	86.8	100
Ref. 35	$10^2 \cdot \kappa_{85}$	0.089	0.121	0.252	0.766	0.855	0.892	0.803
	$10^2 \cdot \kappa_{100}$	0.082	0.116	0.264	0.938	1.125	1.228	1.155

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$AlBr_3$–$ZnBr_2$	p	73.43	78.03	82.57	87.03	91.42		
Ref. **23**	κ_{100}	5.5	5	3	1	0		
	κ_{130}	12.5	10.5	8	—	0		
	κ_{150}	20	17	11	2	0		
$2AlBr_3 \cdot ZnBr_2$	t	100	140	180				
Ref. **28**	$10^3 \cdot \kappa$	5.15	15.12	30.62				
$AlCl_3$–KCl	p	64.73	73.30	80.11	81.55	89.14		
Ref. **21**	κ_{200}	—	0.200	0.165	0.157	0.105		
	κ_{250}	0.346	0.280	0.228	0.214	0.143		
	κ_{300}	0.458	0.357	0.290	(0.270)	(0.180)		
$AlCl_3$–KCl**	p	50.4	53.7	62.5				
Ref. **31**	κ_{600}	0.790	0.811	0.858				
	κ_{700}	0.900	0.935	1.005				
	κ_{800}	1.010	1.060	1.155				
$AlCl_3 \cdot KCl$	t	250	300	500	600	700	800	
Ref. **31, 21**	κ	0.353	0.479	0.706	0.862	1.018	1.174	
$AlCl_3 \cdot LiCl$**	t	174	184	217	259	303.5	327	351
Ref. **21**	κ	0.354	0.380	0.468	0.553	0.647	0.687	0.731
$AlCl_3$–NaCl**	p	69.78	71.03	72.01	76.06	76.95	81.25	82.51
Ref. **15**, 14, 5	κ_{200}	0.436	0.262	0.280	0.160	0.170	0.090	0.070
	κ_{250}	0.532	0.378	0.380	—	0.300	0.178	—
$AlCl_3$–NH_4Cl	p	71.37	78.89	85.46	90.89			
Ref. **21**	κ_{200}	—	—	0.177	0.114			
	κ_{300}	0.479	0.387	0.302	0.194			
AlF_3–Na_3AlF_6*	p	0	2	4	6	8	10	20
Ref. **72, 65, 39, 34**, 12	κ_{1000}	2.8	2.7	2.7	2.6	2.6	2.5	(2.3)
	κ_{1050}	2.9	2.9	2.8	2.8	2.7	2.6	(2.4)
Al_2O_3–Na_3AlF_6	p	0	3	6	9	12	15	20
Ref. **72, 65, 39, 34**, 80, 12, 4	κ_{1000}	2.8	2.6	2.5	2.3	2.2	2.1	(1.8)
	κ_{1100}	3.0	2.9	2.7	2.6	2.4	2.3	(2.0)
Al_2O_3–Li_3AlF_6—Na_3AlF_6	$p_{Al_2O_3}$	6.4	3.2	8.8	3.6	9.8	4.2	
	$p_{Na_3AlF_6}$	46.8	58.2	64.0	67.6	72.2	76.6	
Ref. **80**	κ_{1000}	3.44	—	3.10	3.24	2.43	2.67	
	$10^3\alpha$	5.2	—	4.7	4.8	5.5	5.4	
	$\kappa_t = \kappa_{1000} + \alpha(t-1000)$							
Al_2O_3–SiO_2	p	3	5.5	8	10	12		
Ref. **81**	a	−0.30	0.08	−0.40	−0.30	−1.00		
	$10^{-3}b$	5.9	5.7	4.1	4.8	3.0		
	$\log \kappa_t = a - b(t+273)$ at 1600–1800							
B_2O_3–BaO	p	30.0	35.0	44.5	49.2	59.7	67.9	
Ref. **50**	κ_{900}	—	—	0.007	0.005	0.002	0.002	
	κ_{1000}	0.10	0.07	0.036	0.024	0.013	0.008	
	κ_{1100}	0.19	0.15	0.089	0.062	0.037	0.026	
	κ_{1200}	0.28	0.23	—	—	—	0.056	
B_2O_3–CaO	p	55.3	59.8	62.8	67.9	73.3		
Ref. **50**	κ_{1000}	—	—	—	0.025	0.013		
	κ_{1100}	—	0.12	0.10	0.069	0.047		
	κ_{1200}	0.23	0.22	0.20	0.151	0.100		
B_2O_3–K_2O	p	61.6	70.6	79.6	89.0	94.8	98.5	
Ref. **75, 42**	κ_{600}	0.016	0.003	—	1.8×10^{-4}	8.3×10^{-5}	1.1×10^{-5}	
	κ_{800}	0.186	0.056	0.022	6.0×10^{-3}	2.2×10^{-3}	2.2×10^{-4}	
	κ_{1000}	0.513	0.309	0.112	3.0×10^{-3}	9.1×10^{-3}	1.1×10^{-3}	

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS – *continued*

B_2O_3–Li_2O	p	79.9	87.1	92.0	95.5	97.2	98.5	
Ref. 75, 42	κ_{700}	0.08	—	—	0.003	0.001	—	
	κ_{800}	0.87	0.10	0.03	0.011	0.004	0.001 2	
	κ_{900}	3.02	0.26	0.10	0.026	0.011	0.002 8	
	κ_{1000}	5.25	0.40	0.17	0.051	0.019	0.005 2	
B_2O_3–Na_2O	p	64.0	68.2	77.6	85.8	94.4	99.1	
Ref. 75, 42	κ_{600}	—	—	—	6.5×10^{-4}	1.5×10^{-4}	1.6×10^{-5}	
	κ_{800}	—	0.33	0.08	0.022	4.8×10^{-3}	3.5×10^{-4}	
	κ_{1000}	1.74	1.32	0.40	0.107	2.1×10^{-2}	1.7×10^{-3}	
B_2O_3–PbO	p	88.2	92.7					
Ref. 69	κ_{650}	5×10^{-7}	4×10^{-7}					
	κ_{750}	2×10^{-5}	0.6×10^{-5}					
	κ_{850}	8.5×10^{-5}	2.0×10^{-5}					
B_2O_3–SrO	p	44.9	49.6	56.8	61.6	65.2	70.0	
Ref. 50	κ_{1000}	—	—	0.019	0.012	0.010	0.005	
	κ_{1100}	0.10	0.08	0.062	0.047	0.036	0.021	
	κ_{1200}	0.21	0.17	—	—	—	—	
$BaBr_2$–KBr	p	0	39.2	55.5	62.5	73.0	88.2	93.4
Ref. 43	κ_{700}	—	1.17	1.03	0.85	0.89	—	—
	κ_{750}	1.63	1.29	1.16	0.96	1.00	0.93	—
	κ_{800}	1.76	1.41	1.27	1.06	1.13	1.06	0.98
	κ_{850}	1.87	1.52	1.39	1.17	1.25	1.19	1.12
$BaCl_2$–$CaCl_2$	p	17.3	32.0	44.6	55.6	65.3	73.8	88.3
Ref. 68	κ_{800}	1.84	1.80	1.76	1.71	1.65	1.62	—
	κ_{900}	2.23	2.15	2.08	2.05	1.98	1.93	1.82
	κ_{1000}	2.57	2.51	2.44	2.38	2.32	2.27	2.14
	κ_{1100}	2.86	2.81	2.74	2.66	2.60	2.56	2.44
$BaCl_2$–$MgCl_2$†	p	13.4	31.0	49.7	73.2	75.7		
Ref. 37	κ_{800}	1.405	1.620	1.70	1.61	1.57		
	κ_{900}	1.590	1.810	1.91	1.83	1.785		
	κ_{1000}	(1.775)	2.000	2.12	2.05	2.000		
$BaCl_2$–NaCl	p	28.4	47.1	59.8	70.4	78.1	84.2	93.4
Ref. 49, 17	κ_{800}	3.00	2.55	2.26	2.00	1.54	1.20	—
	κ_{900}	3.26	2.90	2.68	2.50	2.32	2.25	2.00
	κ_{1000}	3.48	3.14	2.92	2.76	2.64	2.58	2.32
$BaCl_2$–$NaNO_3$	p	1.17	1.98	6.14	9.12			
Ref. 40	κ_{350}	1.124	1.107	1.073	1.024			
	κ_{355}	1.143	1.128	1.093	1.052			
	κ_{360}	1.163	—	—	—			
BaF_2–NaF	p			66.6				
Ref. 11	t	900	950	1 000	1 050	1 100		
	κ	4.027	4.335	4.602	5.051	5.319		
$Ba(NO_2)_2$–KNO_2	p	47.8	59.0	68.3	76.3	83.5	89.6	95.0
Ref. 82	κ_{300}	—	0.494	0.438	0.393	—	—	—
	κ_{310}	—	0.528	0.472	0.428	0.381	—	0.311
	κ_{320}	—	0.560	0.505	0.464	0.415	0.386	0.345
	κ_{330}	—	0.594	0.542	0.498	0.450	0.418	0.377
	κ_{340}	0.670	0.628	0.572	0.534	0.486	0.452	0.411
	κ_{350}	0.702	0.660	0.610	0.570	0.520	0.484	0.445
$Ba(NO_2)_2$–KNO_3	p	26.8	31.3	43.8	54.8	64.5	73.3	81.0
Ref. 83	κ_{320}	—	0.50	—	0.42	—	0.39	—
	κ_{340}	—	0.55	—	0.48	—	0.42	0.40
	κ_{360}	0.65	0.60	0.58	0.55	0.50	0.49	—
	κ_{380}	0.73	0.68	0.62	0.60	—	—	—

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$Ba(NO_2)_2$–$NaNO_2$	p	19.4	39.2	53.9	64.0	73.9	84.5	94.5
Ref. 82	κ_{240}	—	—	0.598	0.488	0.372	0.258	—
	κ_{260}	—	0.852	0.700	0.588	0.464	0.334	0.200
	κ_{280}	1.120	0.957	0.802	0.688	0.554	0.410	0.260
	κ_{300}	1.232	1.064	0.910	0.788	0.646	0.486	0.320
	κ_{320}	1.343	1.170	1.016	0.888	0.738	0.564	0.380
	κ_{340}	1.454	1.275	1.120	0.985	0.828	—	—
$Ba(NO_3)_2$–KNO_2	p	50.1	61.0	70.2				
Ref. 83	κ_{260}	(0.38)	0.30	(0.28)				
	κ_{280}	0.41	0.36	(0.31)				
	κ_{300}	0.49	0.41	0.35				
	κ_{320}	0.55	0.46	0.40				
$BeCl_2$–NaCl	p	39.1	45.2	49.2	58.3	63.6	70.8	83.2
Ref. 58	κ_{300}	—	—	0.69	0.58	0.49	—	—
	κ_{400}	—	1.00	1.10	0.98	0.85	0.56	0.19
	κ_{500}	1.35	1.28	1.38	—	—	—	—
Bi–BiI_3	p	3.8	8.1	13.1	34.7	45.1	58.8	76.4
Ref. 84	κ_{500}	0.5	0.8	2.1	200	600	1 400	3 100
Ca–$CaCl_2$	p	0.22	0.29	0.36	0.47	0.62	0.88	1.10
Ref. 85	κ_{855}	2.50	2.52	2.55	2.58	2.61	2.68	2.73
$CaCl_2$–KCl	p	24.6	40.7	66.0	81.5			
Ref. 37, 3	κ_{800}	1.770	1.500	1.415	1.560			
	κ_{900}	2.035	1.790	1.685	1.890			
$CaCl_2$–$MgCl_2$†	p	10.8	19.0	28.0	41.2	62.1	77.1	
Ref. 37	κ_{700}	(1.18)	1.34	1.47	1.65	(1.79)	(1.87)	
	κ_{800}	1.37	1.53	1.68	1.90	2.07	2.20	
	κ_{900}	1.56	1.72	1.89	2.15	2.35	2.53	
$CaCl_2$–NaCl**	p	0	20	40	60	75	90	100
Ref. 67, 49, 17, 18,	κ_{100}	—	2.78	2.31	1.92	1.71	—	—
8, 6, 3	κ_{800}	3.58	3.10	2.64	2.27	2.09	2.01	2.02
	κ_{900}	3.79	3.37	2.96	2.60	2.40	2.32	2.32
	κ_{1000}	4.00	3.58	3.22	2.92	2.71	2.67	2.68
CaF_2–CaO	p	90.7	92.6	94.5	96.4	98.2	100	
Ref. 55	κ_{1500}	4.3	4.6	5.3	4.2	4.1	3.9	
	κ_{1545}	4.6	4.7	7.2	5.2	4.4	4.1	
CaF_2–Na_3AlF_6	p	0	5	10	20	30	40	
Ref. 65, 39, 26,	κ_{1000}	2.8	2.8	2.7	2.6	2.5	2.4	
34, 12	κ_{1100}	3.0	3.0	3.0	2.9	2.8	2.7	
CaF_2–NaF	p	0	10					
Ref. 4, 11	κ_{1000}	3.15	3.0					
	κ_{1020}	3.3	3.1					
$Ca(NO_3)_2$–KNO_3	p	0	16.9	24.0	34.2	44.8	54.9	65.5
Ref. 22	κ_{300}	—	—	0.375	0.330	0.270	0.195	—
	κ_{350}	0.666	0.570	0.525	0.460	0.390	0.315	0.255
	κ_{400}	0.818	0.705	0.660	0.605	0.522	0.430	0.355
CaO–SiO_2	p	20	30	35	40	45	50	55
Ref. 81	a	2.17	2.19	2.22	2.51	3.19	2.39	2.06
	$10^{-3}b$	5.7	5.7	5.2	5.7	6.7	5.0	4.1
		$\log \kappa_t = a - b/(t+273)$ at 1 600–1 800						
$CdBr_2$–$CdCl_2$	p	0	27.1	49.7	69.0	85.6	100	
Ref. 24	κ_{600}	1.95	1.7	1.5	1.35	1.2	1.05	
	κ_{640}	2.1	1.85	1.65	1.5	1.35	1.25	

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$CdCl_2$–CdI_2	p	0	14.2	33.2	59.9	100		
Ref. 43	κ_{400}	0.22	0.35	—	—	—		
	κ_{500}	0.41	0.56	0.78	—	—		
	κ_{600}	0.66	0.79	1.03	1.32	1.96		
	κ_{700}	0.95	1.05	1.30	1.57	2.09		
$CdCl_2$–KCl	p	40	50	60	70	80	90	100
Ref. 47, 24, 3, 27	κ_{500}	—	1.10	1.11	1.19	1.33	1.52	—
	κ_{600}	—	1.24	1.27	1.36	1.51	1.71	1.96
	κ_{700}	1.55	1.48	1.48	1.60	1.77	1.97	2.18
	κ_{800}	1.81	1.73	1.66	1.78	1.94	2.09	2.25
$CdCl_2$–LiCl	p	0	59.1	81.2	92.9	100		
Ref. 43	κ_{550}	—	—	2.8	2.3	—		
	κ_{650}	6.0	4.1	3.2	2.6	2.1		
	κ_{750}	6.4	4.5	3.5	3.0	2.3		
$CdCl_2$–NaCl	p	43.9	67.6	82.5	92.6	100		
Ref. 24	κ_{550}	(2.25)	1.95	1.9	1.85	1.8		
	κ_{600}	(2.4)	2.15	2.1	2.0	1.9		
	κ_{700}	2.7	2.45	2.4	2.3	2.2		
$CdCl_2$–$PbCl_2$	p	0	20	40	60	80	100	
Ref. 56, 27, 24	κ_{500}	1.44	1.68	—	—	—	—	
	κ_{600}	1.88	1.94	1.97	1.97	1.94	1.88	
	κ_{700}	2.28	2.35	2.36	2.31	2.26	2.20	
$CdCl_2$–TlCl	p	0	10	25	40	60	80	100
Ref. 44, 3	κ_{500}	1.35	1.30	1.12	1.24	1.41	—	—
	κ_{600}	1.70	1.66	1.56	1.52	1.66	1.81	1.97
	κ_{700}	1.95	1.86	1.76	1.72	1.86	1.99	2.10
CdI_2–KI	p	0	19.7	35.5	64.3	75.3	89.8	100
Ref. 43	κ_{300}	—	—	—	0.30	0.31	—	—
	κ_{500}	—	—	—	0.66	0.64	0.57	0.41
	κ_{700}	1.32	1.21	1.09	1.06	0.99	0.89	0.95
	κ_{800}	1.52	1.45	1.29	1.26	—	—	—
$Cd(NO_3)_2$–$CsNO_3$	p	39.4	44.6	54.8	64.5	73.8	82.9	
Ref. 45	κ_{200}	—	—	0.09	0.07	—	—	
	κ_{250}	—	0.17	0.16	0.15	0.12	—	
	κ_{300}	0.26	0.25	0.24	0.23	0.20	0.15	
$Cd(NO_3)_2$–KNO_3	p	36.9	50.0	60.9	70.0	77.8	84.4	
Ref. 46	κ_{200}	—	—	0.14	0.12	0.08	0.04	
	κ_{250}	—	—	0.26	0.23	0.18	0.12	
	κ_{300}	0.46	0.44	0.39	0.35	0.31	0.23	
$Cd(NO_3)_2$–$RbNO_3$	p	15.1	28.6	40.8	51.7	61.6	70.6	78.9
Ref. 46	κ_{200}	—	—	0.12	0.10	0.10	0.08	—
	κ_{250}	—	0.22	0.21	0.20	0.19	0.16	—
	κ_{300}	0.31	0.34	0.32	0.31	0.29	0.26	0.20
$Cd(NO_3)_2$–$TlNO_3$	p	9.0	18.1	27.5	37.1	47.0	57.1	67.4
Ref. 45	κ_{150}	—	—	0.14	0.11	0.08	—	—
	κ_{200}	—	0.29	0.25	0.22	0.17	—	—
	κ_{250}	0.47	0.31	0.38	0.34	0.28	0.23	—
	κ_{300}	0.60	0.54	0.50	0.46	0.40	0.34	0.26
Ce–$CeCl_3$	p	1.05	1.8	2.8	3.4	3.9	4.7	5.3
Ref. 95, 96	κ_{855}	1.56	2.02	2.59	3.26	3.81	4.45	5.35
Ce–CeI_3	p	0.55	1.03	1.43	2.07	2.87	3.7	6.1
Ref. 86	κ_{820}	1.00	1.92	2.74	4.75	8.88	15.5	*c.* 60
CsBr–NaCl	p	8.3	19.5	52.1	59.2			
Ref. 87	κ_{800}	2.40	1.69	1.40	1.21			
	κ_{850}	2.55	1.79	1.50	1.30			

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$CsBr–ZnSO_4$	p	39.8	63.8	79.9				
Ref. 62	κ_{505}	0.03	0.09	0.20				
	κ_{550}	0.05	0.13	0.26				
CsCl–NaBr	p	29.4	52.2	71.0	87.0			
Ref. 87	κ_{800}	2.05	1.61	1.50	1.45			
	κ_{850}	2.15	1.70	1.58	1.55			
$CsCl–TiCl_3$	p	52.1	62.3	72.0	81.5	90.8		
Ref. 88	κ_{800}	0.7	0.7	0.8	0.9	1.2		
CuCl–KCl	p	25.8	42.0	47.6	57.5	76.0	85.9	100
Ref. 47	κ_{450}	—	2.00	2.08	2.23	2.71	2.93	3.32
	κ_{500}	—	2.07	2.15	2.32	2.82	3.06	3.43
	κ_{550}	—	2.18	2.26	2.44	2.94	3.20	3.54
	κ_{600}	2.22	2.32	2.40	2.59	3.08	3.34	3.66
$CuO–V_2O_5$	p	10	30	40	50			
Ref. 74	κ_{800}	0.6	3.2	3.8	5.5			
	κ_{900}	1.4	5.0	6.0	10.0			
	κ_{1000}	2.2	—	—	—			
$Cu_2S–FeS$	p	0	25	35	50	65	75	100
Ref. 60	κ_{1100}	—	9.30	8.20	4.60	3.30	2.20	0.50
	κ_{1300}	1.530	9.40	8.30	5.20	4.60	3.80	1.30
	κ_{1500}	1.490	9.50	8.30	—	—	—	1.70
$Dy–DyCl_3$	p	0.0	0.9	2.7	4.9	7.8	12.0	16.7
Ref. 89	κ_{700}	0.42	0.46	0.54	0.65	0.76	0.90	0.98
$Er–ErCl_3$	p	0.0	1.0	3.0	3.8			
Ref. 89	κ_{820}	0.50	0.55	0.67	0.69			
$FeO–SiO_2$	p	55.9	63.3	68.6	72.4	75.4	78.7	84.9
Ref. 41	κ_{1300}	0.5	0.9	1.4	2.1	3.2	4.2	9.0
	κ_{1400}	0.8	1.6	2.3	4.0	5.0	7.8	—
$FeO–TiO_2$	p	32.6	35.7	56.5	62.1	91.9	97.2	
Ref. 63	κ_{1300}	48	50	40	38	145	—	
	κ_{1400}	48	47	34	33	155	225	
$Fe_2O_3–V_2O_5$	p	15.0	19.4	30.5				
Ref. 74	κ_{900}	1.4	3.8	6.8				
	κ_{1000}	2.0	5.8	11.6				
	κ_{1100}	3.6	10.6	—				
$Gd–GdBr_3$	p	0.0	0.4	1.3	2.3	2.7		
Ref. 89	κ_{820}	0.47	0.58	0.87	1.27	1.46		
$Gd–GdCl_3$	p	0.0	0.3	0.6	1.0			
Ref. 89	κ_{650}	0.41	0.43	0.45	0.49			
$HgBr_2–NH_4Br$	p	61.19	78.63	84.66	89.57	93.64	100	
Ref. 32	κ_{250}	0.4	0.5	0.6(2)	0.6	0.45	0	
	κ_{300}	0.55	0.7	0.8(2)	0.75	0.6	0	
$HgCl_2–HgI_2$	p	0	20	40	50	60	80	100
Ref. 19	κ_{225}	—	0.029 5	0.016 0	0.009 4	0.005 3	—	—
	κ_{250}	—	0.028 1	0.016 0	0.009 7	0.005 6	0.001 1	—
	κ_{300}	0.028 0	0.025 2	0.016 0	0.010 4	0.006 3	0.002 0	0.000 8
$HgCl_2–NH_4Cl$	p	71.42	81.82	83.54	86.12	92.21	93.84	95.31
Ref. 32	κ_{250}	0.7	0.9	0.7	0.8	0.55	0.78	0.4
	κ_{300}	0.95	1.15	1.1	1.15	0.75	1.0	0.6
$HgCl_2–TlNO_3$	p	0	10	20	40	50	60	75
Ref. 19	κ_{225}	0.416	0.344	0.274	0.184	0.150	0.126	—
	κ_{250}	0.476	0.397	0.320	0.226	0.186	0.156	0.100
	κ_{275}	0.536	0.450	0.368	0.269	0.222	0.188	0.126

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

HgI_2–KI	p	73.3	80.4	86.5	91.6	96.1	100	
Ref. 44	κ_{270}	—	0.48	0.64	0.64	0.43	0.03	
	κ_{290}	0.50	0.56	0.69	0.69	0.45	0.03	
	κ_{310}	0.56	0.64	0.75	0.75	—	—	
HgI_2–NH_4I	p	67.64	75.82	82.47	87.98	92.62	96.58	100
Ref. 32	κ_{250}	0.3	0.4	0.5	0.6	0.55	0.37	0.03
	κ_{350}	0.6	0.5	0.73	0.77	0.7	0.4	0.03
HgI_2–$TlNO_3$	p	0	20	40	50	60	80	100
Ref. 19	κ_{250}	0.476	0.302	0.174	0.154	0.136	0.142	—
	κ_{275}	0.536	0.348	0.210	0.182	0.161	0.156	0.0305
	κ_{300}	0.596	0.395	0.248	0.214	0.187	0.171	0.0280
Ho–$HoCl_3$	p	0.0	0.7	3.2	6.3	10.6		
Ref. 89	κ_{800}	0.53	0.56	0.69	0.84	1.05		
K–KBr	p	1	2	3	4	6	8	
Ref. 73	κ_{763}	5.6	11.7	22.4	40.8	104.7	229.2	
	κ_{870}	6.8	16.3	29.5	51.3	129.0	263.0	
K–KCl	p	1	2	4	6	8	10	
Ref. 73	κ_{816}	3.8	6.2	14.1	31.6	64.6	117.5	
K–KF	p	1.35	2.72	4.10	4.80			
Ref. 90	κ_{900}	4.5	6.7	12.0	18.0			
K–KI	p	0.5	1.0	1.5	2.0	—	—	—
Ref. 90, 91	κ_{900}	4.5	8.5	13.5	19.0	—	—	—
	p	0.5	1.2	2.6	13.5	26.0	48.7	64.9
	κ_{700}	3.7	7.9	19.7	500	1 500	4 200	7 300
KBF_4–KF	p	30	40	50	60	70	80	90
Ref. 92	κ_{600}	—	—	—	—	1.0	2.0	1.5
	κ_{700}	—	—	3.0	5.3	6.8	7.2	6.7
	κ_{800}	5.0	8.0	10.0	11.5	12.5	12.8	12.6
KBr–KNO_3	p	0	17.2	37.0	54.1	70.2	86.9	100
Ref. 43	κ_{400}	0.82	0.79	0.78	—	—	—	—
	κ_{600}	1.38	1.34	1.29	1.30	1.31	—	—
	κ_{700}	—	—	—	—	1.53	1.53	—
	κ_{800}	—	—	—	—	1.76	1.76	1.76
KBr–NaCl	p	33.7	57.6	85.9	89.0			
Ref. 93	κ_{800}	2.97	2.51	2.20	1.95			
	κ_{850}	3.05	2.60	2.29	2.05			
KBr–RbCl	p	19.7	39.5	59.5	81.3			
Ref. 94	κ_{770}	1.64	1.64	1.64	1.65			
	κ_{800}	1.70	1.70	1.70	1.72			
	κ_{850}	1.80	1.80	1.80	1.82			
KBr–TlBr	p	2.2	5.3	9.7	18.4	30.3	53.9	72.0
Ref. 97	a	0.489_1	0.441_9	2.008_7	2.390_4	0.475_4	0.808_8	0.426_5
	10^3b	3.239_7	2.957_2	7.546_5	8.864_5	3.284_7	4.267_7	5.332_0
	10^6c	0.835_7	0.499_1	3.845_7	4.904_9	0.845_0	1.478_0	0.865_2
	t range	537–701	473–640	650–762	619–717	626–791	687–796	718–783
				$\kappa_t = a + bt - ct^2$				
KBr–$ZnSO_4$	p	35.8	40.0	44.4	50.2	60.0	64.7	73.0
Ref. 48	κ_{475}	0.10	—	—	0.13	0.21	0.24	0.34
	κ_{500}	0.12	0.15	0.14	0.16	0.25	0.29	0.41
	κ_{550}	0.16	0.21	0.19	0.23	0.33	0.39	0.55
KCl–KI	p	2.8	7.8	13.3	26.8	41.2	64.4	
Ref. 57	κ_{700}	1.31	1.38	1.41	1.48	1.56	1.66	
	κ_{800}	1.52	1.56	1.61	1.70	1.80	1.96	
	κ_{900}	1.66	1.72	1.76	1.88	1.97	2.14	

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

KCl–LiCl**	p	0	28.2	42.6	55.8	72.2	87.6	100
Ref. 57, 10	κ_{500}	—	—	2.31	1.87	—	—	—
	κ_{600}	—	3.51	2.87	2.40	1.90	—	—
	κ_{700}	6.17	4.10	3.42	2.88	2.35	2.04	—
	κ_{800}	6.62	4.56	3.82	3.24	2.72	2.36	2.24
$KCl–MgCl_2$	p	10	20	30	50	60	70	80
Ref. 56, 37, 16,	κ_{600}	—	—	0.97	0.98	0.97	0.98	—
9, 7	κ_{700}	1.10	1.17	1.21	1.24	1.27	1.34	1.48
	κ_{800}	1.33	1.37	1.39	1.44	1.48	1.56	1.76
	κ_{900}	1.50	1.54	1.56	1.62	1.67	1.75	1.87
KCl–NaBr	p	22.0	32.0	51.4	74.0			
Ref. 93	κ_{800}	2.64	2.40	2.29	2.21			
	κ_{850}	2.76	2.53	2.39	2.32			
KCl–NaCl**	p	18.7	32.1	40.6	54.8	64.8	82.9	
Ref. 57, 16, 9, 6, 3	κ_{700}	—	—	2.52	2.35	2.21	—	
	κ_{800}	3.23	2.98	2.85	2.64	2.53	2.34	
	κ_{900}	3.50	3.24	3.11	2.88	2.76	2.56	
KCl–NaI	p	0	8.0	19.8	33.0	49.7	73.6	100
Ref. 43	κ_{600}	—	1.88	1.68	1.54	1.51	—	—
	κ_{700}	2.41	2.20	2.04	1.86	1.84	1.87	—
	κ_{800}	2.68	2.51	2.37	2.16	2.44	2.17	2.22
$KCl–PbCl_2$	p	2.8	4.5	6.1	14.8	20.7	37.9	51.2
Ref. 98, 47, 27, 24	κ_{450}	—	1.176	1.142	1.034	0.937	—	—
	κ_{500}	1.414	1.401	1.345	1.205	1.106	1.038	(1.110)
	κ_{550}	1.645	1.609	1.558	1.364	1.273	1.174	1.230
	κ_{600}	1.868	1.807	1.723	1.515	1.417	1.306	1.350
	κ_{650}	2.086	2.018	1.913	1.684	1.572	1.467	1.519
	κ_{700}	—	—	—	—	1.716	1.624	1.670
KCl–RbBr	p	9.9	22.7	39.8	63.9			
Ref. 94	κ_{770}	1.42	1.58	1.70	1.88			
	κ_{800}	1.50	1.65	1.77	1.98			
	κ_{850}	1.59	1.73	1.89	2.09			
$KCl–SnCl_2$	p	0.0	4.1	8.7	14.1	20.3	27.8	31.9
Ref. 99	κ_{300}	1.115	1.079	0.995	0.865	0.688	0.472	—
	κ_{350}	1.388	1.331	1.215	1.060	0.871	0.645	0.702
$KCl–TiCl_3$	p	32.6	42.0	53.0	65.9	81.4		
Ref. 88	κ_{800}	1.0	1.05	1.3	1.5	1.8		
$KCl–ZnCl_2$	p	0	10.5	17.8	26.3	35.9	52.6	58.7
Ref. 66	κ_{500}	0.09	0.40	0.64	0.70	0.76	0.78	0.79
	κ_{550}	0.16	0.51	0.77	0.82	0.89	0.92	0.95
	κ_{600}	0.26	0.63	0.90	0.95	1.01	1.05	1.09
	κ_{650}	0.37	0.76	1.02	1.06	1.14	1.19	1.24
$KCl–ZnSO_4$	p	19.0	24.0	29.3	33.7	39.8	50.0	56.8
Ref. 48	κ_{475}	—	0.09	0.13	0.16	0.21	0.30	0.36
	κ_{500}	0.09	0.12	0.17	0.21	0.25	0.35	0.41
	κ_{550}	0.14	0.16	0.24	0.27	0.32	0.44	0.51
$K_2Cr_2O_7–KNO_3$	p	0	24.4	42.1	55.5	74.4	87.1	100
Ref. 44	κ_{350}	0.56	0.52	0.42	0.35	0.22	0.17	—
	κ_{400}	0.72	0.66	0.64	0.48	0.34	0.26	0.20
	κ_{475}	0.95	0.88	0.74	0.67	0.52	0.41	0.35
KF–NaCl	p	33.20	49.85	66.54	100			
Ref. 6	κ_{750}	2.6	2.9	3.2	—			
	κ_{850}	3.4	3.6	3.7	4.1			
	κ_{950}	4.2	4.3	(4.4)	4.5			

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

KI–NaCl	p	33.6	55.0	74.1	86.9	94.2	100	
Ref. 43	κ_{600}	—	—	1.56	1.35	—	—	
	κ_{700}	—	2.24	1.87	1.64	1.47	1.32	
	κ_{800}	3.06	2.58	2.20	1.91	1.73	1.52	
KI–$ZnSO_4$	p	47.4	50.9	54.8	60.4	62.9	67.3	
Ref. 48	κ_{440}	—	—	0.11	0.13	0.15	0.21	
	κ_{460}	0.09	0.08	0.13	0.16	0.18	0.24	
	κ_{480}	0.12	0.10	0.15	0.18	0.20	0.28	
K_2MoO_4–MoO_3	p	17.5	27.5	43.0	52.2	60.0	79.4	91.0
Ref. 100	a	−3.660 6	−1.312 0	−1.982 0	−1.208 3	−2.728 0	6.064 4	4.250 6
	10^2b	0.942 8	0.336 5	0.534 5	0.333 3	0.832 9	−1.299 9	−0.853 7
	10^6c	−5.010 1	−1.058 9	−2.442 6	−1.206 1	−5.307 3	8.173 1	5.507 5
	t range	760–869	614–804	654–783	642–794	583–705	882–934	877–995
				$\kappa_t = a + bt + ct^2$				
KNO_2–$NaNO_2$	p	12.0	23.6	32.7	45.1	55.3	74.2	83.3
Ref. 82	κ_{300}	1.262	1.176	1.108	1.052	0.998	—	—
	κ_{340}	1.472	1.380	1.308	1.244	1.185	1.040	—
	κ_{380}	—	1.586	1.510	1.434	1.366	1.204	1.130
	κ_{420}	—	—	—	1.625	1.548	1.365	1.287
	κ_{460}	—	—	—	—	—	1.525	1.442
KNO_3–$LiNO_3$	p	66.0						
Ref. 101	$\kappa_t = -0.3788 + 3.40 \times 10^{-3}t$ at 160–240							
	$\kappa_t = -0.4037 + 3.47 \times 10^{-3}t$ at 240–400							
KNO_3–$NaNO_3$**	p	0	20	40	50	60	80	100
Ref. 19, 101, 79, 1	κ_{300}	—	0.820	0.706	0.652	0.625	0.572	—
	κ_{400}	1.364	1.160	1.024	0.966	0.931	0.874	0.818
	κ_{300}	1.720	1.496	1.351	1.284	1.234	1.178	1.107
KNO_3–$RbNO_3$	p	7.1	18.6	31.4	40.7	56.0	73.3	86.0
Ref. 45	κ_{300}	—	0.40	0.42	—	—	—	—
	κ_{350}	0.51	0.52	0.55	0.57	0.59	0.63	0.64
	κ_{400}	0.63	0.65	0.68	0.70	0.73	0.77	0.79
K_2SO_4–$ZnSO_4$	p	31.6	41.8	52.0				
Ref. 62	κ_{450}	0.04	0.06	0.05				
	κ_{500}	0.06	0.08	0.08				
	κ_{550}	0.07	0.12	0.12				
K_2TaF_7–Ta_2O_5	p	78.0	83.4	89.0	94.5	100.0		
Ref. 102	κ_{800}	0.71	0.80	0.87	0.91	0.92		
	κ_{900}	0.85	0.94	1.00	1.04	1.05		
K_2TiF_6–TiO_2	p	81.9	87.5	92.3	94.5	96.6	98.3	100
Ref. 102	κ_{870}	1.18	1.22	1.28	1.30	1.31	1.39	1.40
	κ_{920}	1.29	1.33	1.37	1.39	1.40	1.48	1.49
K_2WO_4–WO_3	p	37.4	50.5	58.3	67.4	76.6	85.0	92.2
Ref. 103	a	2.815 6	2.880 9	2.311 1	2.356 2	5.493 6	7.543 6	38.80
	10^2b	0.560 1	0.615 0	0.549 2	0.565 0	1.250 1	1.640 2	7.964 6
	10^6c	2.087 5	2.501 1	2.432 4	2.392 3	5.882 2	7.524 8	39.636
	t range	891–1 010	759–912	754–770	674–819	773–955	842–1 016	885–1 029
				$\kappa_t = -a + bt - ct^2$				
La–$LaBr_3$	p	0.0	0.4	1.2	2.5	4.1	5.5	6.5
Ref. 89	κ_{820}	0.70	0.94	1.55	3.15	7.35	15.8	25.9
La–$LaCl_3$	p	0.3	1.1	2.0	3.0	4.6	6.2	
Ref. 85	κ_{910}	1.51	1.84	2.46	3.21	5.02	7.21	
La–LaI_3	p	0.5	1.4	2.4	3.5	4.4		
Ref. 86	κ_{840}	0.87	2.39	5.54	12.2	20.9		

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

Li_3AlF_6–Na_3AlF_6	p	20	30	50	80			
Ref. 80, 65	κ_{1000}	3.05	3.38	3.80	4.33			
	$10^3\alpha$	4.8	4.8	4.8	4.8			
		$\kappa_t=\kappa_{1000}+\alpha(t-1000)$ at 762–936						
Li_2MoO_4–MoO_3	p	19.5	33.9	51.5	60.5	71.3	85.2	91.0
Ref. 100	a	10.4708	7.4905	4.0311	4.6127	2.7958	21.3359	13.2305
	10^2b	2.4981	1.8153	1.0289	1.1832	0.7539	5.3686	3.2259
	10^6c	13.536	9.3589	4.4897	5.2117	2.887	30.734	16.322
	t range	778–917	800–907	768–917	799–945	845–956	764–872	809–908
				$\kappa_t=-a+bt-ct^2$				
$LiNO_3$–$RbNO_3$	p	10.5	16.7	23.8	31.9	52.3	65.2	80.8
Ref. 52	κ_{200}	—	0.20	0.24	—	—	—	—
	κ_{250}	—	0.33	0.36	0.41	0.53	0.61	—
	κ_{300}	0.43	0.47	0.51	0.56	0.72	0.82	0.96
Li_2WO_4–WO_3	p	54.6	59.7	69.0	77.5	85.2	92.3	
Ref. 103	a	6.0152	2.1491	7.4648	0.6063	5.2597	5.7237	
	10^2b	1.3336	0.4558	1.7642	0.1086	1.2773	1.4048	
	10^6c	5.5948	0.3923	7.6694	−1.9898	4.8237	5.7978	
	t range	805–952	769–924	757–938	735–890	716–897	734–907	
				$\kappa_t=-a+bt-ct^2$				
$MgCl_2$–NaCl	p	23.2	39.1	57.2	69.0	81.5	90.3	
Ref. 37, 56, 16, 9	κ_{700}	2.80	2.31	1.97	1.78	1.63	1.39	
	κ_{800}	2.96	2.49	2.16	1.98	1.82	1.57	
	κ_{900}	3.12	2.67	2.35	2.18	2.01	1.75	
MgF_2–Na_3AlF_6	p	5	10					
Ref. 72	k_{950}	—	2.2					
	κ_{975}	2.5	—					
MnO–SiO_2	p	40	50	55	60	65	70	80
Ref. 81	a	2.32	2.26	1.85	2.25	2.94	2.21	2.00
	$10^{-3}b$	4.8	4.1	3.1	3.4	4.6	2.5	1.7
				$\log\kappa_t=a-b/(t+273)$ at 1600–1800				
MoO_3–Na_2MoO_4	p	21.4	26.4	51.2	62.2	71.2	83.7	86.2
Ref. 54	κ_{700}	1.06	1.07	0.86	0.80	0.75	0.63	—
	κ_{800}	1.45	1.41	1.17	1.11	1.08	0.75	0.91
	κ_{900}	—	—	—	—	—	—	1.16
Na–NaBr	p	0.25	0.5	0.75	1.0	1.5	2.0	
Ref. 73	κ_{803}	4.0	6.3	7.4	8.2	—	—	
	κ_{894}	4.8	7.7	9.7	11.5	14.7	17.5	
Na–NaCl	p	0.25	0.5	0.75	1.0	1.5		
Ref. 73	κ_{848}	4.3	4.9	5.3	5.7	6.4		
	κ_{893}	4.4	5.0	5.5	5.9	6.7		
Na–NaI	p	0.4	0.6	1.0	1.3	1.6	2.0	
Ref. 90	κ_{700}	3.7	—	—	—	—	—	
	κ_{800}	4.5	3.5	6.5	—	—	—	
	κ_{900}	5.0	6.5	8.0	10.0	12.2	15.0	
Na_3AlF_6–NaF‡	p	0	20	40	60	80	90	100
Ref. 65, 39, 34, 12	κ_{1000}	5.4	4.9	4.4	3.9	3.3	3.1	2.8
	κ_{1050}	5.7	5.1	4.6	4.0	3.5	3.2	2.9
	κ_{1100}	5.9	5.4	4.8	4.2	3.6	3.3	3.1
$NaBF_4$–NaF	p	40	50	60	70	80	90	
Ref. 92	κ_{500}	—	—	1.5	3.0	3.5	4.0	
	κ_{600}	—	3.0	5.0	6.0	6.5	7.0	
	κ_{700}	—	5.0	8.0	10.0	10.5	10.5	
	κ_{800}	6.5	12.0	14.0	15.0	15.5	15.0	

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

NaBr–NaOH	p	17.7	25.0	30.4	39.8	48.4	52.3	
Ref. 70	κ_{300}	1.18	1.14	1.03	0.95	0.83	0.79	
	κ_{400}	2.00	1.96	1.83	1.75	1.63	1.59	
$NaCl–Na_2CO_3$	p	0	52.45	68.81				
Ref. 6	κ_{700}	—	2.2	2.3				
	κ_{850}	2.4	3.1	3.0				
	κ_{1000}	2.8	3.1	3.4				
$NaCl–NbCl_5$	p	43.8	60.4	60.7	71.8	73.6	100	
Ref. 20	κ_{800}	1.32	2.20	2.19	—	—	3.34	
	κ_{850}	1.83	2.60	2.59	2.98	2.94	3.60	
$NaCl–PbCl_2$	p	0	2.55	9.01	20.05			
Ref. 17	κ_{500}	1.445	1.51	1.58	1.645			
	κ_{600}	1.91	1.95	2.005	2.07			
$NaCl–TiCl_3$	p	27.5	36.2	47.0	60.3	77.4		
Ref. 88	κ_{800}	1.75	1.75	1.9	2.3	2.7		
$NaCl–ZrCl_4$	p	11.5	34.9	59.7	75.1	88.1	88.7	
Ref. 20, 104	κ_{350}	0.46	—	—	—	—	—	
	κ_{800}	—	1.45	1.74	2.41	2.88	2.68	
	κ_{825}	—	—	1.83	2.83	3.08	—	
	κ_{850}	—	—	1.97	3.01	3.34	3.36	
$NaF–SrF_2$	p	—	—	33.3	—	—		
Ref. 11	t	900	950	1 000	1 050	1 100		
	κ	4.441	4.798	4.961	5.407	5.642		
NaI–NaOH	p	21.5	35.0	44.8	52.8			
Ref. 70	κ_{300}	1.14	0.87	0.72	0.63			
	κ_{400}	1.90	1.53	1.32	1.23			
$NaNO_2–NaNO_3$	p	0	21.3	44.8	65.4	82.1	100	
Ref. 43	κ_{300}	—	1.02	1.11	1.19	1.25	1.34	
	κ_{350}	1.16	1.27	1.34	1.44	1.51	1.62	
	κ_{400}	1.36	1.51	1.58	1.69	1.78	1.89	
	κ_{450}	1.55	1.73	1.79	1.92	2.02	2.10	
$Na_2O–TiO_2$	p	28.3	41.7	44.6	51.7	60.0	65.5	71.6
Ref. 64	κ_{1000}	—	0.32	0.38	0.47	0.56	0.70	0.86
	κ_{1100}	0.32	0.45	0.56	0.80	0.90	0.94	1.15
	κ_{1200}	0.74	1.03	1.16	1.55	1.76	2.10	2.54
$Na_2WO_4–WO_3$	p	45.9	50.9	55.7	65.1	74.2	83.0	91.6
Ref. 103	a	4.4509	7.0013	4.5634	7.2754	3.1368	6.0743	2.7481
	10^2b	0.9625	1.5476	1.0326	1.7201	0.7399	1.5506	0.6718
	10^6c	4.0364	7.0320	4.4555	8.5600	2.4220	7.1943	2.4958
	t range	780–923	750–888	767–905	741–881	689–850	653–803	701–869
				$\kappa_t = -a + bt - ct^2$				
Nd–$NdBr_3$	p	0.4	1.5	3.6	7.5	11.4	13.9	15.4
Ref. 89	κ_{730}	0.53	0.61	0.79	0.94	1.01	0.96	0.92
Nd–$NdCl_3$	p	1.7	2.4	3.8	7.3	11.0	14.6	18.6
Ref. 85	κ_{855}	1.20	1.24	1.32	1.54	1.67	1.77	1.84
Nd–NdI_3	p	0.3	0.9	2.1	5.2	8.1	11.1	11.5
Ref. 86	κ_{820}	0.476	0.585	0.759	1.033	1.102	0.980	0.930
$PbBr_2$-$PbCl_2$	p	0	23.7	45.3	66.6	83.8	100	
Ref. 59, 3	κ_{450}	—	—	1.02	0.97	0.91	0.84	
	κ_{500}	1.43	1.34	1.25	1.17	1.10	1.03	
	κ_{550}	1.69	1.56	1.45	1.36	1.26	1.19	

Table 9.5 ELECTRICAL CONDUCTIVITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

PbO–SiO_2	p	61.4	71.2	78.8	84.8	89.7	93.7	97.1
Ref. 105	log κ_{900}	−2.9	−2.0	−1.2	−0.7	−0.3	0.0	0.2
	log κ_{1150}	−1.9	−1.2	−0.6	−0.2	0.0	0.2	0.6
Pr–$PrBr_3$	p	0.5	1.1	2.5	4.1	5.8	8.6	8.7
Ref. 89	κ_{740}	0.66	0.80	1.10	1.47	1.90	2.38	2.67
Pr–PrI_3	p	0.3	1.3	2.6	4.2	6.3	8.1	8.9
Ref. 86	κ_{780}	0.61	1.28	2.48	4.24	8.25	14.8	21.0
RbCl–$TiCl_3$	p	43.9	54.0	64.6	75.8	87.6		
Ref. 88	κ_{800}	0.95	0.95	1.0	1.2	1.4		
VCl_2 in KCl–NaCl	p	9.6	12.8	17.9	22.4	29.7	39.7	52.0
(equi-molar:	κ_{600}	0.22	0.48	2.34 (610)	1.30	1.18 (605)	1.46	0.050
56.1% KCl)	κ_{800}	3.68 (810)	3.77 (790)	3.94 (790)	3.94	3.85	3.68 (795)	2.93 (805)
Ref. 106								

* *See also* Na_3AlF_6–NaF.
** *See also* 'Physical Properties Data Compilations Relevant to Energy Storage II Molten Salts: Data on Single and Multi-Component Salt Systems', J. Janz *et al.*, NSRDS-NBS 61, Part II.
† Melts may contain up to 1% MgO.
‡ *See also* AlF_3–Na_3AlF_6.

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Table 9.6 SURFACE TENSION OF PURE MOLTEN SALTS
The surface tension (mNm^{-1}) at temperature t (°C) is given as γ_t, or the constants a, b and t_0 in the equation $\gamma_t = a - b(t - t_0)$ are given for the temperature range r. Principal references are in **bold type.**

AgBr	γ_{500}	152
Ref. **16, 1**	γ_{600}	148
	γ_{700}	146
AgCl	γ_{500}	176
Ref. **16, 5**	γ_{600}	171
	γ_{700}	166
AgI	γ_{600}	115
Ref. **16**		
$AgNO_3$	a	152.1
Ref. **22**, 27, 19	b	0.082
	t_0	212
	r	244–400
Al_2O_3	γ_{2050}	700
Ref. **28**		
B_2O_3	γ_{700}	67
Ref. **21**	γ_{1000}	83
	γ_{1300}	99
$BaBr_2$	γ_{900}	150
Ref. **20**	γ_{950}	147
	γ_{1000}	143
$BaCl_2$	γ_{966}	169.2
Ref. **23**, 15, 12, 9, 2	γ_{979}	168.3
	γ_{984}	168.6
	γ_{996}	168.1
	γ_{1000}	167.8
	γ_{1050}	164
$Ba(NO_3)_2$	a	134.8
Ref. **22**	b	0.015
	t_0	595
	r	600–660
$BiBr_3$	γ_{250}	66
Ref. **6**	γ_{350}	56
	γ_{450}	45
$BiCl_3$	γ_{275}	67
Ref. **6**	γ_{325}	59
	γ_{375}	53
BrF_3	γ_{12}	37
Ref. **18**	γ_{27}	36
	γ_{45}	34
BrF_5	γ_9	24
Ref. **18**	γ_{33}	22
$CaBr_2$	γ_{780}	117.31
Ref. **20**	γ_{800}	116.39
$CaCl_2$	γ_{800}	150.57
Ref. **28, 29**	γ_{1000}	140.07
CaI_2	γ_{800}	85
Ref. **20**	γ_{900}	83
	γ_{1000}	81
$Ca(NO_3)_2$	γ_{560}	101.5
Ref. **22**		
$CdBr_2$	γ_{600}	67
Ref. **16**	γ_{700}	65
$CdCl_2$	γ_{600}	83
Ref. **16**	γ_{700}	81
	γ_{800}	78
CsBr	γ_{650}	82.5
Ref. **28, 29**	γ_{800}	73.35
	γ_{1000}	61.147
CsCl	γ_{700}	87.50
Ref. **29, 6**, 12	γ_{900}	71.18
	γ_{1100}	54.86
CsF	γ_{700}	106.1
Ref. **28, 29**	γ_{900}	92.26
	γ_{1100}	78.46
CsI	γ_{650}	73.47
Ref. **28**, 29	γ_{800}	64.77
	γ_{1000}	53.17
$CsNO_3$	a	92.5
Ref. **22**, 6	b	0.069
	t_0	414
	r	421–597
Cs_2SO_4	γ_{1000}	114.25
Ref. **30**	γ_{1250}	98.84
	$\gamma_{15..}$	83.75
FeO	γ_{1400}	584.0
Ref. **28**		
$GaCl_2$	a	56.6
Ref. **24**	b	0.18
	t_0	170
	r	166–170
$GaCl_3$	γ_{80}	27
Ref. **17**	γ_{110}	24
	γ_{140}	21
GeO_2	γ_{1000}	241
Ref. **21**	γ_{1200}	253
	γ_{1400}	265
$HgBr_2$	γ_{241}	64
Ref. **8**	γ_{276}	60
$HgCl_2$	γ_{293}	56
Ref. **8**		
IF_5	γ_{18}	31
Ref. **18**	γ_{28}	28
KBr	γ_{750}	90
Ref. **16, 11, 6**, 27	γ_{800}	86
	γ_{850}	82
	γ_{900}	78
KCl	γ_{800}	98
Ref. **19, 16, 15, 12, 9, 6**,	γ_{900}	90
27	γ_{1000}	82
	γ_{1100}	75

Table 9.6 SURFACE TENSION OF PURE MOLTEN SALTS—*continued*

$K_2Cr_2O_7$	γ_{420}	140.28
Ref. 30	γ_{470}	138.28
	γ_{520}	136.28
KF	γ_{900}	138.12
Ref. 28, 29, 30	γ_{1100}	123.12
	γ_{1300}	108.12
KI	a	138.7
Ref. 27	b	0.087
	t_0	0
	r	(m.p. + 10)–(m.p. + 210)
K_2MoO_4	γ_{900}	151.47
Ref. 30	γ_{1200}	132.87
	γ_{1500}	114.27
KNO_2	a	107.6
Ref. 22	b	0.080
	t_0	435
	r	445–501
KNO_3	γ_{350}	108.61
Ref. 27	γ_{450}	102.21
	γ_{600}	92.61
	γ_{800}	79.81
KPO_3	γ_{900}	193.54
Ref. 30	γ_{1200}	171.94
	γ_{1500}	150.34
K_2SO_4	γ_{1100}	143
Ref. 13	γ_{1300}	130
	γ_{1500}	116
K_2WO_4	γ_{900}	162.41
Ref. 30	γ_{1200}	134.51
	γ_{1500}	106.61
La_2O_3	γ_{2320}	560
Ref. 7		
LiCl	γ_{600}	137.14
Ref. 28, 29	γ_{800}	123.22
	γ_{1000}	109.30
LiF	γ_{850}	250.46
Ref. 28, 29	γ_{1050}	228.60
	γ_{1250}	206.74
$LiNO_2$	a	115.4
Ref. 22, 6	b	0.053
	t_0	255
	r	276–425
Li_2SO_4	γ_{900}	223
Ref. 13, 6	γ_{1000}	216
	γ_{1100}	209
	γ_{1200}	202
NH_4NO_3	a	101.9
Ref. 22	b	0.105
	t_0	170
	r	170–220.
Na_3AlF_6	γ_{1000}	134.06
Ref. 31	γ_{1010}	132.78
	γ_{1020}	131.50
NaBr	γ_{750}	106
Ref. 16, 6, 27	γ_{800}	103
	γ_{950}	92
	γ_{1150}	79
NaCl	γ_{800}	116.42
Ref. 6, 27	γ_{900}	107.12
	γ_{1000}	97.82
	γ_{1100}	88.52
NaF	γ_{1000}	185.21
Ref. 6, 31	γ_{1200}	168.81
	γ_{1400}	152.41
	γ_{1500}	144.21
NaI	a	147.4
Ref. 27	b	0.090
	t_0	0
	r	(m.p. + 10)–(m.p. + 210)
Na_2MoO_4	γ_{700}	211.68
Ref. 30	γ_{900}	196.28
	γ_{1100}	180.88
	γ_{1200}	173.18
$NaNO_2$	a	121.2
Ref. 22, 27	b	0.041
	t_0	277
	r	291–384
$NaNO_3$	γ_{310}	116.21
Ref. 27	γ_{400}	112.70
	γ_{500}	108.80
	γ_{600}	104.90
$NaPO_3$	γ_{800}	200.74
Ref. 6, 30	γ_{1000}	186.34
	γ_{1200}	171.94
	γ_{1500}	150.34
Na_2SO_4	γ_{900}	193
Ref. 13, 6	γ_{950}	190
	γ_{1000}	186
	γ_{1050}	183
Na_2WO_4	γ_{700}	201.46
Ref. 6, 30	γ_{1000}	182.0
	γ_{1300}	162.46
	γ_{1600}	143.0
$PbCl_2$	γ_{500}	137.12
Ref. 27	γ_{600}	126.12
	γ_{700}	115.12
P_2O_5	γ_{100}	60
Ref. 21	γ_{200}	58
	γ_{400}	54
RbBr	γ_{700}	99.77
Ref. 28, 29	γ_{900}	88.17
	γ_{1100}	76.57

Table 9.6 SURFACE TENSION OF PURE MOLTEN SALTS—*continued*

RbCl	γ_{750}	94.90
Ref. **28, 29**	γ_{900}	82.49
	γ_{1000}	74.22
	γ_{1150}	61.82
RbF	γ_{800}	163.83
Ref. 28, 29	γ_{900}	153.60
	γ_{1000}	143.37
RbI	γ_{700}	76.86
Ref. **28, 29**	γ_{900}	63.18
	γ_{1000}	56.34
$RbNO_3$	γ_{300}	109.53
Ref. **32**	γ_{500}	95.53
	γ_{700}	81.53
Rb_2SO_4	γ_{1100}	130.8
Ref. **30**	γ_{1300}	120.4
	γ_{1500}	110
SiO_2	γ_{1000}	278
Ref. **21**	γ_{1500}	295
	γ_{2000}	313
$SnCl_2$	γ_{300}	96.74
Ref. **28, 29**	γ_{400}	88.44
	γ_{500}	80.14
$SrBr_2$	γ_{700}	147
Ref. **20**	γ_{800}	143
	γ_{900}	138
	γ_{1000}	134
$SrCl_2$	γ_{900}	168
Ref. **20**	γ_{950}	165
	γ_{1000}	162
SrI_2	γ_{600}	112
Ref. **20**	γ_{750}	106
	γ_{850}	102
	γ_{950}	98
$Sr(NO_3)_2$	γ_{615}	128.4
Ref. **22**		
$TlNO_3$	a	94.8
Ref. **22, 6**	b	0.078
	t_0	206
	r	226–458
Tl_2S	a	215.6
Ref. **25**	b	0.0356
	t_0	445
	r	500–700
V_2O_5	γ_{1000}	86
Ref. **26**		

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Table 9.7 SURFACE TENSION OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS
The surface tension (mN m^{-1}) at temperature t(°C) and composition p(wt.%) of the first-named constituent is given as γ_t (or σ_t), or the constants a, b and t_0 in the equation $\gamma_t = a - b(t - t_0)$ are given for the temperature range r. Principal references are in **bold type.**

AgBr–AgCl	p	0	24.7	46.7	66.4	84.0	100
Ref. **16**	σ_{500}	176	169	164	158	155	152
	σ_{600}	171	164	160	155	152	148
AgBr–AgI	p	0	16.7	34.8	54.5	76.2	100
Ref. **16**	σ_{500}	—	122	127	133	141	152
	σ_{600}	115	118	123	130	138	148
AgBr–KBr	p	0	28.3	51.3	70.3	86.3	100
Ref. **16**	σ_{700}	—	96	99	104	113	146
	σ_{750}	90	92	96	101	110	146
AgCl–KCl	p		32.6	56.3	72.6	88.6	100
Ref. **16**	σ_{600}		112	117	123	136	171
	σ_{700}		105	110	117	129	166
AgCl–$PbCl_2$	p	0	11.4	25.6	43.7	67.4	100
Ref. **16**	σ_{500}	137	139	144	150	160	176
	σ_{600}	127	129	134	142	152	171
$AgNO_3$–$CsNO_3$	p	22.5	46.5	72.4	88.8		
Ref. **19**	a	126.1	130.3	140.1	148.4		
	b	0.075	0.072	0.073	0.072		
	t_0	0	0	0	0		
	r		liquidus–c. 400				
$AgNO_3$–KNO_3	p	20	40	60	80	95	100
Ref. **18**, 24. 19	σ_{250}	—	—	124	129	139	147
	σ_{300}	—	118	121	126	136	144
	σ_{350}	113	114	117	122	133	140
$AgNO_3$–$LiNO_3$	p	45.0	71.2	88.1	100		
Ref. **19**	a	137.8	145.7	153.5	163.7		
	b	0.064	0.068	0.067	0.066		
	t_0	0	0	0	0		
	r		liquidus–c. 400				
$AgNO_3$–$NaNO_3$	p	24.1	33.3	60.0	75.0	90.0	95.0
Ref. **18**, 24, 19	σ_{300}	—	—	126	130	136	137
	σ_{350}	119	120	123	127	133	135
	σ_{400}	115	116	—	—	—	—
$AgNO_3$–$RbNO_3$	p	27.8	53.5	77.7	91.3		
Ref. **19**	a	134.0	136.9	143.4	151.7		
	b	0.077	0.073	0.070	0.069		
	t_0	0	0	0	0		
	r		liquidus–c. 400				
AlF_3–Na_3AlF_6	p	2.5	5	10	15		
Ref. **11**, 1	σ_{1000}	142	137	127	118.		
Al_2O_3–FeO	p	5.6	6.9				
Ref. 4	σ_{1410}	598	604				
Al_2O_3–Na_3AlF_6	p	2.5	5	10	15		
Ref. **11**, 1	σ_{1000}	143	140	136	134		

Table 9.7 SURFACE TENSION OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

B_2O_3–BaO	p	20.5	34.6	44.4	54.7	64.2	75.1	84.5
Ref. 14	σ_{900}	—	—	239	197	146	88	79
	σ_{1100}	315	257	229	187	138	92	87
	σ_{1300}	294	243	221	181	135	106	96
B_2O_3–CaO	p	51.2	62.8	73.3	83.1	93.7	98.1	
Ref. 14	σ_{900}	—	—	176	—	81	81	
	σ_{1100}	302	235	150	87	87	88	
	σ_{1300}	297	221	140	96	95	96	
B_2O_3–K_2O	p	51.5	55.7	65.6	75.3	84.9	94.8	98.5
Ref. 13	σ_{700}	—	—	—	140	107	80	75
	σ_{900}	139	153	160	143	112	85	80
	σ_{1100}	—	—	149	142	118	93	88
B_2O_3–Li_2O	p	71.3	79.9	87.1	92.0	95.5	100	
Ref. 13	σ_{700}	—	221	—	120	84	74	
	σ_{900}	231	207	158	121	92	80	
	σ_{1100}	—	—	152	125	101	88	
B_2O_3–Na_2O	p	64.0	73.6	82.2	85.8	94.4	99.1	
Ref. 13	σ_{700}	—	196	146	—	83	77	
	σ_{900}	197	185	147	130	91	81	
	σ_{1100}	—	—	149	134	99	89	
B_2O_3–PbO	p	0	15.9	33.6	50.9	65.6	78.4	100
Ref. 10, 8	σ_{700}	—	162	160	—	—	—	—
	σ_{900}	132	163	144	92	78	79	80
	σ_{1000}	135	163	—	—	—	—	83
B_2O_3–SrO	p	35.4	49.6	61.6	70.0	89.0	96.0	
Ref. 14	σ_{900}	—	—	194	137	80	—	
	σ_{1100}	303	247	178	123	87	86	
	σ_{1300}	292	237	166	122	95	93	
B_2O_3–ZnO	p	20.5	29.4	35.4	41.4	50.0	90.0	100
Ref. 9	σ_{900}	—	—	235	184	80	78	80
	σ_{1100}	—	283	232	179	88	86	86
	σ_{1300}	355	287	238	185	—	95	94
$BaCl_2$–KCl	p	0	20.4	47.4	59.0	67.2	82.2	92.8
Ref. 15	σ_{850}	93	98	106	110	114	129	—
	σ_{900}	89	94	103	106	112	128	144
	σ_{950}	—	—	—	—	—	121	141
$BaCl_2$–Li_2SO_4	p	0	9.0	17.3	44.6	65.3	84.9	100
Ref. 6	σ_{1000}	220	198	192	167	163	161	175
	σ_{1050}	216	190	180	164	158	159	172
$BaCl_2$–NaCl	p	0	28.4	47.1	65.7	78.1	93.4	100
Ref. 3, 20	σ_{900}	107	109	117	126	133	160	—
	σ_{1000}	100	103	111	120	126	154	171
$CaCl_2$–NaCl*	p	0	17.4	44.8	65.5	88.3	100	
Ref. 3	σ_{800}	114	115	121	126	137	148	
	σ_{1000}	100	100	108	116	125	140	
CaF_2–Na_3AlF_6	p	2.5	5	10	15			
Ref. 11	σ_{1000}	149	150	152	155			
CaO–FeO	p	0	5.5	15.4	22.3			
Ref. 4	σ_{1410}	585	555	543	573			
$CdBr_2$–$CdCl_2$	p	0	20.9	41.3	61.7	80.9	100	
Ref. 16	σ_{600}	83	78	74	71	68	67	
	σ_{700}	81	76	72	68	66	65	

Table 9.7 SURFACE TENSION OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$CdCl_2$–KCl	p		38.1	62.1	78.7	90.7	100	
Ref. 16	σ_{600}		100	93	90	88	82	
	σ_{700}		94	87	84	84	81	
$CdCl_2$–NaCl	p	0	44.0	67.6	82.5	92.6	100	
Ref. 16	σ_{700}	—	108	98	90	85	81	
	σ_{800}	114	101	92	85	81	78	
$CdCl_2$–$PbCl_2$	p	0	14.1	31.8	49.7	72.4	100	
Ref. 16	σ_{600}	126	116	107	98	90	83	
	σ_{700}	116	108	101	93	87	81	
Cr_2O_3–FeO	p	0	3.1					
Ref. 4	σ_{1420}	585	588					
CsCl–Li_2SO_4	p	0	1.6	3.2	4.8	15.2	61.8	100
Ref. 7, 6	σ_{900}	224	205	193	189	163	102	72
	σ_{1000}	220	201	188	185	160	92	64
	σ_{1100}	211	194	181	177	154	—	—
CsCl–$PbCl_2$	p	12.4	27.4	38.6	49.0	64.7		
Ref. 18	σ_{500}	116	—	—	—	103		
	σ_{600}	—	97	—	93	94		
	σ_{625}	—	94	91	90	92		
$CsNO_3$–KNO_3	p	39.1	66.0	85.3				
Ref. 19	a	133.7	129.4	125.1				
	b	0.079	0.077	0.074				
	t_0	0	0	0				
	r		liquidus–c.	400				
$CsNO_3$–$LiNO_3$	p	48.5	73.9	89.4				
Ref. 19	a	124.3	124.3	122.9				
	b	0.070	0.076	0.075				
	t_0	0	0	0				
	r		liquidus–c.	400				
$CsNO_3$–$NaNO_3$	p	43.1	67.6	87.3				
Ref. 19	a	130.5	127.3	123.4				
	b	0.068	0.074	0.072				
	t_0	0	0	0				
	r		liquidus–c.	400				
Cs_2O–SiO_2	p	47.2	54.0	69.0	78.9			
Ref. 21	γ_{1300}	166.1	165.1	144.3	120.5			
	γ_{1400}	163.8	162.5	—	—			
FeO–MnO	p	90.5	94.0	100				
Ref. 4	σ_{1410}	555	567	585				
FeO–SiO_2	p	68.1	76.9	84.1	95.8	100		
Ref. 4	σ_{1410}	409	468	503	563	585		
FeO–TiO_2	p	81.9	85.1	100				
Ref. 4	σ_{1410}	510	522	585				
KBr–KCl	p	0	28.6	51.7	70.7	86.5	100	
Ref. 16	σ_{750}	—	97	95	93	92	90	
	σ_{800}	99	95	93	89	87	86	
KBr–NaBr	p	0	22.4	43.5	63.4	82.2	100	
Ref. 16	σ_{700}	—	103	98	96	95	—	
	σ_{800}	103	96	92	88	87	86	
KBr–Na_2SO_4	p	0	4.2	21.8	45.6	100		
Ref. 5	σ_{900}	193	181	140	116	81		

Table 9.7 SURFACE TENSION OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$KCl–K_2SO_4$	p	0	0.9	2.2	4.5			
Ref. 7	σ_{1075}	144	140	135	133			
$KCl–Li_2SO_4$	p	0	7.0	26.6	40.2	66.8	85.8	100
Ref. 7, 6	σ_{900}	224	182	145	128	109	97	91
	σ_{1000}	220	178	142	123	101	90	85
	σ_{1100}	211	173	135	116	92	81	75
$KCl–MgCl_2$	p	8.0	16.4	34.4	54.1	75.9	87.6	
Ref. 17	σ_{700}	76	79	83	85	93	97	
	σ_{800}	69	72	76	78	86	90	
	σ_{900}	62	65	69	71	79	83	
KCl–NaCl*	p	0	24.2	46.0	65.6	83.6	100	
Ref. 18, 17, 3	σ_{700}	—	—	114	111	—	—	
	σ_{750}	—	115	111	107	104	—	
	σ_{800}	114	111	107	104	101	96	
KCl–NaI	p	7.9	19.5	32.6	49.0	73.2	84.9	
Ref. 24	a	135.2	128.0	121.7	124.4	127.2	128.5	
	b	0.066	0.063	0.057	0.063	0.069	0.070	
	t_0	0	0	0	0	0	0	
	r		(m.p. + 10) – (m.p. + 210)					
$KCl–Na_2SO_4$	p	0	2.7	14.8	34.2	100		
Ref. 5	σ_{900}	193	183	153	129	92		
$KCl–PbCl_2$	p	0	5.5	15.2	28.6	51.7		
Ref. 18, 16	σ_{500}	137	125	118	117	118		
	σ_{600}	117	114	109	107	107		
$KI–Na_2SO_4$	p	0	5.8	11.5	28.0	53.9	100	
Ref. 5	σ_{900}	193	177	157	127	100	73	
$KNO_2–KNO_3$	p	17.4	35.8	55.9	77.0			
Ref. 24	a	129.6	131.3	130.6	131.8			
	b	0.059	0.061	0.055	0.052			
	t_0	0	0	0	0			
	r		(m.p. + 10)–(m.p. + 210)					
$KNO_3–LiNO_3$	p	0	32.9	59.5	81.5	100		
Ref. 19	a	129.9	127.9	129.6	133.6	139.8		
	b	0.055	0.056	0.062	0.070	0.081		
	t_0	0	0	0	0	0		
	r		liquidus–c. 400					
$KNO_3–NaNO_3$*	p	0	40	60	100			
Ref. 18, 16, 19	σ_{350}	117	115	114	112			
	σ_{400}	114	112	111	109			
	σ_{450}	111	109	107	105			
$KNO_3–RbNO_3$	p	0	18.6	40.7	67.4			
Ref. 19	a	134.3	135.0	136.9	138.5			
	b	0.083	0.082	0.083	0.083			
	t_0	0	0	0	0			
	r		liquidus–c. 400					
$K_2O–SiO_2$	p	23.9	26.7	29.9	32.9	38.7	43.6	
Ref. 12, 21	σ_{1000}	—	227	227	227	225	—	
	σ_{1200}	222	223	220	219	218	215	
	σ_{1400}	219	219	216	214	210	206	
$K_2SO_4–RbCl$	p	92.9	96.5	98.6	100			
Ref. 7	σ_{1075}	134	139	141	143			
$LiCl–PbCl_2$	p	6.1	7.8	12.8	13.4	24.9	27.1	
Ref. 18	σ_{500}	133	134	134	133	—	—	
	σ_{550}	130	129	129	129	128	—	
	σ_{600}	124	—	—	—	—	124	

Table 9.7 SURFACE TENSION OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

LiCl–RbCl	p	0	75.9	86.9	91.9	94.5	97.2	100
Ref. 7	σ_{750}	96	113	118	119	121	122	127
Li_2O–SiO_2	p	12.9	17.8	23.9	27.8	33.5	43.1	49.1
Ref. 12, 21	σ_{1100}	—	315	328	338	—	—	—
	σ_{1300}	311	317	328	334	352	369	381
	σ_{1400}	316	317	328	332	349	364	374
$LiNO_3$–$RbNO_3$	p	13.5	31.8	58.3				
Ref. 19	a	130.0	129.6	125.0				
	b	0.075	0.074	0.059				
	t_0	0	0	0				
	r		liquidus–c. 400					
Li_2SO_4–NaCl*	p	0	38.8	65.5	81.6	94.5	98.7	100
Ref. 7, 6	σ_{900}	109	131	148	168	198	208	224
	σ_{1000}	104	125	143	164	194	204	220
	σ_{1100}	95	116	134	157	187	196	211
Li_2SO_4–RbCl	p	0	38.0	57.9	68.1	78.6	89.2	100
Ref. 7, 6	σ_{900}	83	105	126	140	155	179	224
	σ_{1000}	74	97	120	134	149	174	220
	σ_{1100}	66	92	114	—	145	168	211
$MgCl_2$–NaCl	p	17.9	33.0	56.7	74.7	88.7	94.7	
Ref. 17	σ_{700}	110	103	95	87	79	75	
	σ_{800}	104	97	89	81	73	69	
	σ_{900}	98	91	83	75	67	63	
Na_3AlF_6–NaF	p	85	90	95	97.5			
Ref. 11, 1	σ_{1000}	161	159	155	152			
NaCl–$NaNO_3$	p	0	9.2					
Ref. 5	σ_{470}	110	110					
NaCl–Na_2SO_4	p	0	0.8	1.7	4.3			
Ref. 7	σ_{900}	192	189	184	179			
NaCl–$PbCl_2$	p	0	4.9	11.7	15.1	18.2		
Ref. 18, 3, 24	σ_{500}	—	133	131	—	—		
	σ_{550}	131	127	124	—	—		
	σ_{575}	128	124	122	122	122		
NaF–$NaNO_3$	p	0	9.8					
Ref 5	σ_{560}	108	108					
NaI–$NaNO_3$	p	0	10.1					
Ref. 5	σ_{312}	119	119					
Na[illegible]–Na_2SO_4	p	0.5	1.1	2.1	3.2	5.3	10.5	
Ref. 2	σ_{900}	168	167	160	158	154	141	
$NaNO_2$–$NaNO_3$	p	16.9	35.4	55.0	76.3			
Ref. 24	a	127.9	127.1	128.9	126.8			
	b	0.039	0.035	0.038	0.030			
	t_0	0	0	0	0			
	r		(m.p. + 10) – (m.p. + 210)					
$NaNO_3$–$RbNO_3$	p	16.1	36.5	63.4				
Ref. 19	a	132.5	133.7	135.4				
	b	0.076	0.073	0.068				
	t_0	0	0	0				
	r	liquidus–c. 400						
Na_2O–P_2O_5	$\gamma_t = 150.6 + 155p/(100-p) - 0.0379t$							
Ref. 22	r_p	30.4–39.5						
	r_t	liquidus–1 050						

Table 9.7 SURFACE TENSION OF MOLTEN BINARY SALTS SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

Na_2O–SiO_2	p	20.0	30.8	33.6	36.9	50.0		
Ref. 12, 2, 21	σ_{1000}	277	284	286	288	—		
	σ_{1200}	276	280	281	283	295		
	σ_{1400}	273	274	274	276	284		
Na_2SO_4RbCl	p	0	1.7	3.4	4.3	8.6		
Ref. 7	σ_{1050}	183	173	171	169	162		
$PbCl_2$–RbCl	p	46.7	62.8	69.0	83.1	90.3	98.2	
Ref. 7	σ_{475}	—	112	112	116	124	—	
	σ_{525}	—	107	107	111	118	130	
	σ_{575}	104	104	104	107	113	124	
PbO–SiO_2	p	65.1	69.9	75.7	82.5	84.7	90.6	96.8
Ref. 8, 23	σ_{900}	—	—	217	199	192	174	134
	σ_{1100}	234	232	221	204	196	179	145
	σ_{1300}	235	230	223	209	—	183	158
PbO–V_2O_5	p	15.3	39.6	52.8	65.4	79.0	85.1	92.1
Ref. 23	γ_{1000}	92	135	168	174	205	202	192
PbO–SiO_2–V_2O_5	p_{PbO}	28.5	38.6	58.4	60.0	68.5	80.0	
Ref. 23	p_{SiO_2}	10.3	10.4	10.4	10.1	10.6	10.0	
	γ_{1000}	128	142	150	190	210	202	
Rb_2O–SiO_2	p	39.1	43.9	49.5	59.5	67.3		
Ref. 21	γ_{1200}	—	—	—	175.1	155.0		
	γ_{1300}	200.1	192.7	188.0	173.4	146.3		
	γ_{1400}	197.1	188.8	183.5	170.9	—		

* *See also:* 'Physical Properties Data Compilations Relevant to Energy Storage II Molten Salts: Data on Single and Multi-Component Salt Systems', J. Janz *et al.*, NSRDS–NBS 61, Part II.

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Table 9.8 VISCOSITY OF PURE MOLTEN SALTS

The viscosity (centipoise) at temperature t(°C) is given as η_t, or the constants a and b in the equation $\log \eta_t = a + b/(t+273)$ are given for the temperature range r. Principal references are in **bold type**.

AgBr	η_{450}	3.3
Ref. **22, 11, 9**	η_{550}	2.4
	η_{650}	1.7
	η_{800}	1.2
AgCl	η_{500}	2.05
Ref. **22, 11, 9**	η_{600}	1.60
	η_{700}	1.25
	η_{800}	1.05
AgI	η_{600}	3.0
Ref. **11, 9**	η_{700}	2.3
	η_{800}	1.7
$AgNO_3$	η_{230}	4.10
Ref. **25, 21, 17, 11, 9**	η_{280}	3.05
	η_{330}	2.40
	η_{350}	2.20
B_2O_3	η_{600}	158 000
Ref. **24, 20, 4**	η_{800}	25 100
	η_{1000}	6 300
	η_{1200}	2 000
$BaCl_2$	η_{1000}	4.506
Ref. **2, 6**		
$BiCl_3$	η_{260}	32
Ref. **5**	η_{300}	23
	η_{340}	18
$CaCl_2$	η_{800}	3.021
Ref. **6, 7**	η_{900}	1.870
	η_{1000}	1.248
$CdBr_2$	η_{600}	2.60
Ref. **18**	η_{640}	2.35
	η_{680}	2.10
$CdCl_2$	η_{600}	2.35
Ref. **23, 18, 14**	η_{700}	1.85
	η_{800}	1.55
CuCl	η_{500}	2.80
Ref. **14**	η_{600}	1.95
	η_{700}	1.40
$HgBr_2$	η_{255}	2.196
Ref. **8, 13**	η_{265}	2.008
	η_{275}	1.843
$HgCl_2$	η_{281}	1.768
Ref. **32**	η_{287}	1.738
	η_{292}	1.694
	η_{299}	1.600
	η_{306}	1.543
HgI_2	η_{268}	2.669
Ref. **32**	η_{292}	2.244
	η_{314}	1.995
	η_{334}	1.715
	η_{358}	1.458
KBr	η_{750}	1.150
Ref. **7, 14, 16**	η_{800}	1.022
	η_{900}	0.831
KCl	η_{800}	1.094
Ref. **14, 16, 26**	η_{900}	0.841
	η_{1000}	0.673
$K_2Cr_2O_7$	η_{400}	13.79
Ref. **27, 29**	η_{450}	9.665
	η_{500}	7.091
KI	η_{750}	1.362
Ref. **30**	η_{800}	1.205
	η_{900}	0.973
KNO_2	a	−0.87
Ref. **33**	b	960
	r	418–450
KNO_3	η_{350}	2.705
Ref. **27, 16, 31, 34, 35**	η_{400}	2.090
	η_{450}	1.673
	η_{550}	1.163
KOH	η_{400}	2.3
Ref. **10**	η_{500}	1.3
	η_{600}	0.8
LiBr	η_{550}	1.815
Ref. **7, 14**	η_{700}	1.096
	η_{850}	0.757
LiI	η_{450}	2.50
Ref. **14**	η_{550}	1.70
	η_{650}	1.30
$LiNO_3$	η_{260}	5.5
Ref. **17, 12, 11, 3**	η_{300}	4.0
	η_{350}	2.9
Na_3AlF_6	η_{1007}	6.7
Ref. **19**	η_{1017}	6.5
	η_{1050}	6.0
NaBr	η_{762}	1.345
Ref. **14, 16**	η_{766}	1.332
	η_{780}	1.288
NaCl	η_{800}	1.463
Ref. **16, 34, 35**	η_{900}	1.009
	η_{1000}	0.737
NaI	η_{650}	1.581
Ref. **30**	η_{750}	1.168
	η_{900}	0.818
$NaNO_2$	a	−1.07
Ref. **33**	b	868
	r	282–310
$NaNO_3$	η_{300}	3.156
Ref. **31, 34, 36, 37**	η_{400}	1.901
	η_{500}	1.305
NaOH	η_{350}	4.0
Ref. **10**	η_{450}	2.2
	η_{550}	1.5
$NaPO_3$	η_{650}	1 250
Ref. **28, 4**	η_{750}	440
	η_{850}	210
	η_{900}	150
$PbBr_2$	η_{360}	10.5
Ref. **22, 17, 1**	η_{400}	7.3
	η_{450}	5.0
	η_{550}	3.0
$PbCl_2$	η_{500}	4.6
Ref. **22, 1**	η_{600}	2.8
	η_{700}	1.9
$TlNO_3$	a	−1.04
Ref. **33**	b	565
	r	207–250

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Table 9.9 VISCOSITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS

The viscosity (centipoise) at temperature t(°C) and composition p(wt.%) of the first-named constituent is given as η_t, or the constants a and b in the equation $\log \eta_t = a + b/(t + 273)$ are given for the temperature range r. Principal references are in **bold type**.

AgBr–AgCl	p	0	32.5	46.7	66.9	84.0	100
Ref. **12**	η_{440}	—	2.58	2.75	2.97	3.12	3.38
	η_{520}	1.98	2.10	2.18	2.35	2.46	2.69
	η_{600}	1.68	1.74	1.74	1.98	2.09	2.28
AgBr–KBr	p	57.1	66.0	78.0	86.0	100	
Ref. **12**	η_{400}	—	—	3.55	3.55	—	
	η_{500}	—	2.55	2.40	2.46	2.83	
	η_{600}	1.73	1.74	1.78	1.86	2.27	
AgCl–KCl	p	54.3	61.1	80.4	88.9	100	
Ref. **12**	η_{500}	—	—	2.10	2.12	2.08	
	η_{600}	1.63	1.61	1.56	1.62	1.66	
	η_{700}	1.28	1.24	1.24	1.28	1.40	
AgCl–$PbCl_2$	p	0	9.8	24.1	44.5	67.6	100
Ref. **12**	η_{500}	4.56	4.13	3.47	2.95	2.47	2.08
	η_{600}	2.75	2.59	2.30	2.12	1.84	1.66
	η_{700}	1.87	1.99	1.84	1.76	1.65	1.40

Table 9.9 VISCOSITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

AgI–$AgNO_3$	p	0	25.7	47.9	67.4			
Ref. 17	η_{150}	—	9.6	13.6	19.6			
	η_{200}	..	6.4	8.6	12.6			
	η_{250}	4.2	5.2	6.5	8.7			
	η_{300}	3.8	4.8	5.5	7.0			
$AgNO_3$–HgI_2	p	9.8	13.8	19.9	27.2	35.9	46.6	56.2
Ref. 15, 21	η_{110}	..	2.3	—	—	19.5	13.8	9.6
	η_{150}	3.2	..	7.4	7.0	5.6	4.2	3.2
	η_{200}	1.5	2.3	2.4	2.2	1.9	1.8	1.4
$AgNO_3$–KNO_3	p	29.6	41.9	52.8	62.7	71.6	79.7	83.5
Ref. 14, 21	η_{150}	—	—	..	18.2	19.1	18.1	—
	η_{200}	..	—	—	8.9	9.6	9.2	8.9
	η_{250}		7.4	6.4	5.6	6.0	6.4	6.0
	η_{300}	5.8	5.1	4.8	4.1	4.3	4.6	4.5
AlF_3–Na_3AlF_6	p	2.5	5	10	15			
Ref. 7	η_{1000}	6.5	6.3	5.7	4.8			
Al_2O_3–Na_3AlF_6	p	2.5	5	10	15			
Ref. 7	η_{1000}	6.9	6.9	7.1	10.9			
B_2O_3–BaO	p	44.5	49.2	54.9	59.7	64.4	67.9	
Ref. 10	η_{850}	—	30 900	35 500	35 500	33 900	25 100	
	η_{900}	2 750	6 170	8 710	9 550	9 550	7 080	
	η_{950}	980	1 900	3 160	3 710	3 240	2 950	
	η_{1000}	—	—	—	1 260	1 260	1 180	
B_2O_3–K_2O	p	61.6	70.6	84.9	89.0	94.8	98.5	100
Ref. 9	η_{600}	6.8×10^5	5.1×10^6	—	1.5×10^5	0.9×10^5	1.3×10^5	1.6×10^5
	η_{800}	780	4 680	4 360	3 900	5 130	13 800	21 400
	η_{900}	—	960	1 350	1 290	2 400	6 310	11 500
	η_{1000}	—	—	—	450	1 120	3 710	6 460
B_2O_3–Li_2O	p	85.2	87.1	92.0	95.5	97.2	100	
Ref. 9	η_{600}	—	—	—	355 000	141 000	158 000	
	η_{800}	3 630	3 020	5 370	3 630	7 240	21 400	
	η_{900}	460	520	790	980	3 090	11 500	
	η_{1000}	—	—	250	320	1 440	6 460	
B_2O_3–Na_2O	p	68.2	69.2	77.6	85.8	94.4	99.1	100
Ref. 9	η_{600}	—	3.1×10^6	—	1.9×10^6	1.3×10^5	1.3×10^5	1.6×10^5
	η_{800}	930	1 290	6 920	5 890	3 800	12 000	21 400
	η_{900}	—	—	870	1 380	1 580	5 750	11 500
	η_{1000}	..	—	—	—	810	2 630	6 460
B_2O_3–$NaPO_3$	p	0	50	95	99.5			
Ref. 18	η_{900}	150	450	4 730	11 000			
$BaCl_2$–NaCl	p	45.5	55.6	63.8	70.5	75.3	80.1	84.4
Ref. 19, 5, 21	η_{725}	—	3.2	3.42	4.05	4.6	—	..
	η_{775}	2.40	2.58	2.82	3.22	3.48	3.70	3.85
	η_{825}	2.00	2.23	2.50	2.80	3.00	3.15	3.28
	η_{875}	1.75	2.02	2.36	2.55	2.72	2.84	3.05
BaO·SiO_2	p	31.7	46.1	53.1	63.2	71.7		
Ref. 16	η_{1500}	—	11 000	3 200	1 700	..		
	η_{1700}	19 500	2 140	850	540	190		
	η_{1800}	10 000	1 250	530	400	150		
$CaCl_2$·NaCl*	p	0	17.4	44.8	65.5	88.3	100	
Ref. 5, 19	η_{800}	1.59	1.65	2.59	3.49	4.36	4.92	
	η_{900}	1.00	1.16	2.11	2.95	3.69	4.22	
	η_{1000}	0.70	1.00	1.79	2.60	3.31	3.74	
CaF_2–Na_3AlF_6	p	2.5	5	10	15			
Ref. 7	η_{1000}	6.9	7.0	7.3	8.0			

Table 9.9 VISCOSITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

$CaO–SiO_2$	p	29.1	37.1	41.9	47.9	51.9	55.9	
Ref. 11, 3	η_{1500}	—	1 440	765	—	288	—	
	η_{1600}	—	730	405	218	157	113	
	η_{1700}	1 360	392	235	133	96	74	
	η_{1800}	850	250	150	88	66	54	
$CdBr_2–CdCl_2$	p	0	27.2	49.9	69.1	85.6	100	
Ref. 6	η_{600}	2.3	2.4	2.4	2.5	2.5	2.6	
	η_{660}	2.0	2.0	2.1	2.1	2.1	2.2	
$CdCl_2–KCl$	p	40.3	59.5	67.3	71.9	82.4	88.8	100
Ref. 13	η_{500}	—	2.53	2.54	2.62	2.97	3.17	—
	η_{600}	1.76	1.67	1.67	1.73	1.92	2.15	2.31
	η_{700}	1.23	1.21	1.20	1.24	1.40	1.57	1.83
$CdCl_2–NaCl$	p	53.9	75.8	79.0	82.5	90.2	100	
Ref. 13	η_{500}	—	2.68	2.71	2.84	2.99	—	
	η_{600}	—	1.78	1.80	1.88	2.02	2.31	
	η_{700}	1.37	1.30	1.27	1.39	1.50	1.83	
$CdCl_2–PbCl_2$	p	0	18.0	26.8	37.9	65.9	100	
Ref. 13	η_{520}	4.22	3.75	3.50	3.36	—	—	
	η_{600}	2.75	2.60	2.47	2.38	2.26	2.31	
	η_{680}	2.00	2.02	1.88	1.85	1.85	1.90	
$KCl–MgCl_2$	p	37.6	48.5	58.9	59.9	69.1	78.8	
Ref. 2, 21	η_{500}	3.26	—	2.78	2.69	—	—	
	η_{600}	2.19	1.55	1.51	1.70	1.44	—	
	η_{700}	—	1.22	—	—	0.99	1.25	
KCl–NaCl*	p	0	56.0	79.3	100			
Ref. 5	η_{800}	1.59	1.17	1.07	1.13			
	η_{900}	1.00	0.90	0.81	0.89			
$KCl–PbCl_2$	p	0	5.2	8.8	18.3	21.8	34.7	43.3
Ref. 13	η_{500}	4.56	4.02	3.66	3.34	3.37	—	—
	η_{600}	2.75	2.42	2.27	2.06	2.10	2.15	—
	η_{700}	1.87	1.65	1.56	1.42	1.47	1.48	1.50
$K_2O–SiO_2$	p	3.9	9.5	15.9	23.9	29.9	38.7	43.6
Ref. 16, 8	η_{1000}	—	—	—	32 800	15 100	7 940	4 570
	η_{1200}	—	—	—	2 240	1 350	661	355
	η_{1400}	—	—	—	372	200	81	47
	η_{1600}	468 000	107 000	24 000	—	—	—	—
$Li_2O–SiO_2$	p	12.0	16.1	21.8	25.9	28.9	33.2	37.9
Ref. 16, 8	η_{1100}	—	50 100	12 000	4 470	—	—	—
	η_{1300}	42 700	8 320	2 190	1 000	510	220	72
	η_{1400}	17 800	3 890	1 120	580	300	140	52
	η_{1500}	8 320	2 040	710	400	200	100	41
$MgO–SiO_2$	p	34.8	35.5	36.2	40.1	41.4		
Ref. 16	η_{1650}	610	460	350	250	190		
	η_{1750}	360	270	200	150	120		
	η_{1800}	280	210	180	120	110		
$Na_3AlF_6–NaF$	p	85	90	95	97.5			
Ref. 7	η_{1000}	4.8	5.9	6.4	6.7			
$NaCl–NaNO_3$	p	1.4	2.8	4.2	5.7	7.1	8.6	10.1
Ref. 19	η_{310}	3.20	3.27	3.68	—	—	—	—
	η_{350}	2.57	2.67	2.79	2.83	3.00	—	—
	η_{400}	2.06	2.21	2.32	2.18	2.11	2.20	2.39
	η_{450}	1.72	1.91	1.98	1.96	1.94	1.73	2.18
$Na_2O–P_2O_5$	p	30.4	32.0	36.0	39.6	43.3	46.5	48.4
Ref. 20	a	−0.84	−0.63	−0.26	0.11	0.38	0.58	0.59
	$10^{-3}b$	3.57	3.19	2.45	1.87	1.45	1.10	1.00
	r	741–1 013	707–1 001	657–1 017	822–1 002	942–1 064	1 030–1 077	995–1 070

Table 9.9 VISCOSITY OF MOLTEN BINARY SALT SYSTEMS AND OTHER MIXED IONIC MELTS—*continued*

Na_2O–SiO_2	p	15.2	20.0	30.8	36.9	40.9	45.2	50.0
Ref. 16, 8, 4, 1	η_{900}	—	4.6×10^6	2.4×10^5	3.2×10^5	1.8×10^5	—	—
	η_{1100}	—	263 000	50 100	26 900	15 100	4 070	890
	η_{1300}	118 000	33 100	7 940	4 270	2 340	690	160
	η_{1400}	41 700	16 600	4 900	2 570	1 350	390	100
$PbBr_2$–$PbCl_2$	p	0	28.4	63.1	80.2	100		
Ref. 12	η_{450}	—	—	5.53	5.24	4.83		
	η_{500}	4.56	4.45	4.03	3.94	3.73		
	η_{550}	3.54	3.38	3.14	3.05	2.97		
SiO_2–SrO	p	36.4	42.0	46.0	57.8	62.9	69.7	
Ref. 16	η_{1650}	47	360	620	1 380	4 220	—	
	η_{1750}	160	210	370	780	2 240	5 820	
	η_{1800}	130	180	300	580	1 660	4 300	

* *See also* 'Physical Properties Data Compilations Relevant to Energy Storage II, Molten Salts, Data on Single and Multi-Component Salt Systems', Janz *et al.*, NSRDS–NBS, 61.

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10 Metallography

Metallography can be defined as the study of the structure of materials and alloys by the examination of specially prepared surfaces. Its original scope was limited by the resolution and depth of field in focus by the imaging of light reflected from the metallic surface. These limitations have been overcome by both transmission and scanning electron microscopy (TEM, STEM and SEM). The analysis of X-rays generated by the interaction of electron beams with atoms at or near the surface, by wavelength or energy dispersive detectors (WDX, EDX), has added quantitative determination of local composition, e.g. of intermetallic compounds, to the deductions from the well-developed etching techniques. Surface features can also be studied by collecting and analysing electrons diffracted from the surface. A diffraction pattern of the surface can be used to determine its crystallographic structure (low-energy electron diffraction or LEED). These electrons can also be imaged as in a conventional electron microscope (low-energy electron microscopy or LEEM). This technique is especially useful for studying dynamic surface phenomena such as those occurring in catalysis. X-ray photoelectron microscopy (XPS or ESCA) now enables the metallographer to analyse the atoms in the outermost surface layer to a depth of a few atoms (0.3–5.0 nm) and provides information about the chemical environment of the atom. Auger spectroscopy uses a low-energy electron beam instead of X-rays to excite atoms, and analysis of the Auger electrons produced provides similar information about the atoms from which the Auger electron is ejected.

Nevertheless, the conventional optical techniques still have a significant role to play and their interpretation is extended and reinforced by the results of the electronic techniques.

10.1 Macroscopic examination

For examination of large-scale features—grain structure of castings, coarse grain in wrought products, porosity in castings, major defects, or distribution of alloying elements and impurities on a large scale (e.g. to study 'segregation') it is necessary to prepare large surfaces free from major distortion, but extreme smoothness and structural perfection are not required.

The required section is cut by sawing, abrasive slitting wheels or machining with adequate cooling and lubrication, and is normally finished by fine machining, followed by etching if necessary. Grinding on abrasive cloth or paper, which may be followed by polishing with proprietary metal polish, is sometimes beneficial, but vigorous polishing, especially with power-driven machines, may cause the metal to flow over defects such as porosity. Examination for porosity is usually best carried out on a fine machined surface.

The final machining operation should be done with a single sharp tool, for instance by planing, turning or milling with a fly-cutter, rather than by the use of a milling cutter. For soft metals (e.g. copper, lead, pure aluminium) the shape of the tool is important; it should have a rounded nose and adequate front clearance to prevent rubbing, and it should have a large top rake (the softer the metal, the larger the rake required) so that it presents almost a chisel edge to the specimen. For harder metals more orthodox tools may be used.

Illumination of unetched specimens for photomacrographs to show porosity requires a broad source of illumination. The sky (without direct sunlight) is sometimes the most suitable source.

Etching reagents for macroscopic work are listed in Table 10.1. Directions for 'sulphur-printing', to show the distribution of sulphide in steel, are included.

10.2 Microscopic examination

Metallographic specimens are normally prepared for examination under the microscope by cutting out the piece to be examined (preferably not more than 3 cm dia.), carefully removing the disturbed surface layer (by turning or filing with a sharp tool) and then rubbing the surface with successively finer abrasives until a smooth polished surface is obtained, sensibly free from

disturbing effects from the cutting and grinding; the clean, smooth, undistorted surface is then attacked chemically, or otherwise, by etching reagents which reveal the structure of the metal. Any mechanical method of cutting or smoothing the surface produces distortion of the metal near the surface, and it may produce local heating; the objective is to make the disturbed layer successively thinner at each stage until it is negligible or can be removed by etching. The thickness of the disturbed layer is in the range 10–100 μm for emery or silicon carbide papers with hand grinding. Some or all of the mechanical grinding and polishing can often he replaced by chemical of electrochemical polishing methods, by which the metal is attacked in such a way that protuberances are preferentially dissolved and the flat undisturbed metal surface is laid bare, usually with a saving of time and frequently with an improvement in result.

For some purposes, e.g. study of slip processes involving individual dislocations, electron microscopical studies of fine structure, and quantitative microhardness testing under light loads, electro-polishing is almost indispensable. In general, the type of finish required varies somewhat with the magnification to be used in examination. High-power examination demands great perfection of small areas, but relatively large-scale undulations, such as may sometimes occur on electropolished specimens, are unimportant. At lower powers detail may be less important, but widely spaced imperfections and undulations are liable to become obtrusive.

Table 10.1 ETCHING REAGENTS FOR MACROSCOPIC EXAMINATION

Material	*Reagent**		*Remarks*
A. *Aluminium base*			
1. Aluminium and its alloys	(a) Concentrated Keller's Reagent		Can be diluted with up to 50ml water
	Nitric acid (1.40)	100ml	
	Hydrochloric acid (1.19)	50ml	
	Hydrofluoric acid (40%)	1½ml	
	(b) Nitric acid (1.40)	30ml	Widely applicable, but very vigorous
	Hydrochloric acid (1.19)	30ml	
	2% conc. hydrofluoric acid	30ml	
	(c) Tucker's Reagent		Use fresh
	Nitric acid (1.40)	15ml	
	Hydrochloric acid (1.19)	45ml	
	Hydrofluoric acid (40%)	15ml	
	Water	25ml	
	(d) 10% sodium hydroxide in water		Use at 60–70°C
2. Unalloyed aluminium and Al–Cn alloys	(e) Flick's Reagent		
	Hydrochloric acid	15ml	Wash in warm water after etching and clear by dipping in concentrated nitric acid
	Hydrofluoric acid	10ml	
	Water	90ml	
3. Aluminium–silicon	(f) Hume-Rothery's Reagent		For high-silicon alloys. Fine polish undesirable. Immerse specimen 5–10s, remove, and brush away deposited copper or remove it with 50% nitric acid in water
	Cupric chloride	15g	
	Water	100ml	
4. Aluminium–copper	(g) Keller's Reagent		More frequently used as micro-etch
	2½% nitric acid (1.40)		
	1½% hydrochloric acid (1.19)		
	½% hydrofluoric acid (40%)		
	Rem. water		
5. Aluminium–magnesium	(h) 5% cupric chloride		Clear surface with strong nitric acid
	3% nitric acid (1.40)		
	Rem. water		
6. Aluminium–copper–silicon	(g) Keller's Reagent (as above)		
	(i) Nitric acid (1.40)	15ml	
	Hydrochloric acid (1.19)	10ml	
	Hydrofluoric acid (40%)	5ml	
	Water	70ml	
7. Aluminium–copper–magnesium–nickel	(j) Zeerleder's Reagent		
	Hydrochloric acid (1.19)	20ml	
	Nitric acid (1.40)	15ml	
	Hydrofluoric acid (40%)	5ml	
	Water	60ml	

* Acids are concentrated, unless otherwise indicated, e.g. with specific gravity.

Table 10.1 ETCHING REAGENTS FOR MACROSCOPIC EXAMINATION—*continued*

Material	*Reagent**		*Remarks*
B. *Copper base*			
1. Copper and copper alloys generally	(a) Alcoholic ferric chloride		
	Ethyl alcohol	96 ml	Avoid use of water for washing or staining may result. Use alcohol or acetone instead. Grain contrast
	Ferric chloride (anhydrous)	59 g	
	Hydrochloric acid (1.19)	2 ml	
	(b) Acid aqueous ferric chloride		
	Ferric chloride	25 g	(a) and (b) require moderately high standard of surface finish
	Hydrochloric acid (1.40)	25 ml	
	Water	100 ml	
	(c) Concentrated nitric acid (140)		A rapid etch suitable for roughly prepared surfaces. Addition of a trace of silver nitrate (5%) enhances contrast
	Nitric acid (1.40)	50 ml	
	Water	50 ml	
	(d) 10% ferric chloride in water	10 ml	To reveal strains in brasses
	5% chromium trioxide in saturated brine	10 ml	
	20% acetic acid in water	20 ml	
	(e) A. 1% mercuric nitrate in distilled water		Time required to induce cracks is indication of residual stress
	B. 1% nitric acid (1.40) in water		
	Mix A and B in equal proportions		
	(f) Chromium trioxide	40 g	Good for alloys with silicon and silicon bronzes
	Ammonium chloride	7.5 g	
	Nitric acid (1.40)	50 ml	
	Sulphuric acid (1.84)	8 ml	
	Distilled water	100 ml	
C. *Iron and steel*			
	(a) 50% hydrochloric acid in water		Use hot (70–80°C) for up to 1 h. Shows segregation, porosity, cracks useful for examination of welds for soundness
	(b) 20% sulphuric acid in water		Use hot (80°C) for 10–20 min. Scrub lightly to remove carbonaceous deposit. Purpose as (a). Mixtures of (a) and (b) are also used similarly
	(c) 25% nitric acid in water		Purposes as (a) and (b). May be used cold if more convenient
	(d) 10% ammonium persulphate in water		Grain contrast etch. Apply with swab. Reveals grain growth and recrystallization at welds.
	(e) Stead's Reagent		For revealing phosphorus segregation and primary dendritic structure of cast steels. Dissolve the salts in the acid with addition of a minimum of water. Phosphorus segregate unattacked, also eutectic cells in cast iron
	Cupric chloride	10 g	
	Magnesium chloride	40 g	
	Hydrochloric acid (1.19)	20 ml	
	Alcohol to 1 litre		
	(f) Fry's Reagent		
	Cupric chloride	90 g	To reveal strain lines in mild steel. Heat specimen to 150–250°C for 15–30 min before etching. Etch for 1–3 min while rubbing with a soft cloth. Rinse with alcohol.
	Hydrochloric acid	120 ml	
	Water	100 ml	
	(g) Humphrey's Reagent		Reveals dendritic structure of cast steels. First treat surface with 8% copper ammonium chloride solution and then with (g) for $\frac{1}{2}$–$1\frac{1}{2}$ h. Remove copper deposit (loosely adherent), dry and rub surface lightly with abrasive
	Copper ammonium chloride	120 g	
	Hydrochloric acid (1.19)	50 ml	
	Water	1 litre	
	(h) 5–10% nitric acid in alcohol		Etch for up to $\frac{1}{2}$ h. Reveals cracks and carbon segregation. More controlled than aqueous acids
	(j) Sulphur-printing		Soak photographic printing paper in the acid and remove surplus acid with blotting paper. Lay paper face down on the clean steel surface and
	3% sulphuric acid in water		

* Acids are concentrated, unless otherwise indicated, e.g. with specific gravity.

Table 10.1 ETCHING REAGENTS FOR MACROSCOPIC EXAMINATION—*continued*

Material	*Reagent**		*Remarks*
C. *Iron and steel—continued*			'squeegee' into close contact. After 2 min remove paper, wash it and fix in 6% sodium thiosulphate in water. Brown coloration on the paper indicates local segregation of sulphides
	(k) Dithizone process for lead distribution		*See* p. 10.38, *Lead in steels.* Analogous to sulphur-printing
	(l) Marble's Reagent		Austenitic steels. High temperature steels. Fe–Cr–Ni casting alloys. Also shows depth of nitriding
	Hydrochloric acid (1.19)	50 ml	
	Saturated aqueous solution of cupric sulphate	25 ml	
	(m) Oberhoffer's Reagent		Good surface preparation needed. Steel castings. Darkens Fe-rich areas, reveals segregation and primary cast structure
	Hydrochloric acid (1.19)	42 ml	
	Ferric chloride	30 g	
	Stannous chloride	0.5 g	
	Water	500 ml	
	Ethanol	500 ml	
	(acid added last)		
	Rinse in 20% hydrochloric acid in ethanol		
	(n) Klemm's Reagent		Phosphorus distribution in cast steel and cast iron. Grain contrast
	Saturated aqueous solution of sodium thiosulphate	50 ml	
	Sodium metabisulphite (can be increased for contrast)	1 g	
D. *Lead base*			
Lead and lead alloys generally	(a) Russell's Reagent		Grain contrast etch; removes deformed layer
	A. 80 ml nitric acid (1.40) in 220 ml water		Mix equal parts of A and B immediately before use. Swab for 10–30 s
	B. 45 g ammonium molybdate in 300 ml water		Rinse in water
	(b) Ammonium molybdate	10 g	Bright etch revealing grain structure, defects, etc.
	Citric acid	25 g	
	Water	100 ml	
	(c) Worner and Worner's Reagent		Chemical polish revealing defects, etc.
	Acetic acid, glacial '100 vol.'	75 ml	Specimen must be dry and water content of solution as low as possible
	hydrogen peroxide	25 ml	*N.B.*—Avoid all heating, as lead alloys recrystallize very readily
	(d) Nitric acid (1.40)	20 ml	Immerse 5–10 min. Grain contrast, laminations, welds. Up to 50% nitric acid can be used
	Water (distilled)	80 ml	
	(e) Glacial acetic acid	20 ml	Macrostructure of alloy with Ca, Sb and Sn. Use fresh only. Several minutes needed
	Nitric acid (1.40)	20 ml	
	Glycerol	80 ml	
	(f) Glacial acetic acid	20 ml	2–10 s by swabbing. Good for alloys with Bi, Te or Ni
	Nitric acid (1.40)	20 ml	
	Hydrogen peroxide (30%)	20 ml	
	Water (distilled)	50 ml	
E. *Magnesium base*	(a) Picric acid (64%) saturated in ethanol (96%)	50 ml	Grain size. Flow lines in forging (wash precipitate in hot water). Etch for up to 3 min
	Glacial acetic acid	20 ml	
	Distilled water	20 ml	
	(b) Ammonium persulphate	2 ml	Flow lines in forgings
	Distilled water	98 ml	
	(c) Nitric acid (1.40)	20 ml	Internal defects in casts. Useful for Mg–Mn and Mg–Zr. Etch for up to 3 min
	Water	80 ml	
	(d) Glacial acetic acid	10 ml	General defects; flow lines, segregation. Etch for up to 3 min
	Water	90 ml	
F. *Nickel base*			
	(a) Nitric acid (1.40)	50 ml	Welds, Ni–Cr–Fe alloys
	Acetic acid	50 ml	

* Acids are concentrated, unless otherwise indicated, e.g. with specific gravity.

Table 10.1 ETCHING REAGENTS FOR MACROSCOPIC EXAMINATION—*continued*

Material	*Reagent**		*Remarks*
F. *Nickel base—continued*			
	(b) Aqua regia		As (a) *See also* ref. 1. p. 10.69
	Nitric acid (1.19)	25 ml	
	Hydrochloric acid (1.19)	75 ml	
G. *Tin base*			
	(a) Sat. soln of ammonium polysulphide in water (wipe off surface film)		Grain structure; suitable most tin alloys (etching time 20–30 min)
	(b) FeCl	10 g	Sn–Sb alloys (up to 3 min)
	Hydrochloric acid (1.18)	2 ml	
	Water	100 ml	
H. *Zinc base*			
Zinc and zinc alloys	(a) Concentrated hydrochloric acid (1.19)		Good grain contrast
Zinc-rich alloys	(b) 5% hydrochloric acid in alcohol		HCl can be increased to 50%. Wash under running water to remove reaction products
	(c) Sodium sulphate (3.5 g if hydrated)	1.5 g	Better than above for Zn–Cu alloys
	Chromium trioxide	20 g	
	Water	100 ml	
I. *Other metals*			
Many of these require etching in agressive solutions comprising various mixtures of HCl, HNO_3 and HF	(a) Hydrochloric acid (1.18)	50 ml	Platinum metals group, especially Ru, Os, Rh
	Nitric acid (1.40)	20 ml	
	Hydrofluoric acid (40%)	30 ml	
	(b) Hydrochloric acid (1.19)	30 ml	Cr, Mo, W, V, Nb, Ta
	Nitric acid (1.40)	15 ml	
	Hydrofluoric acid (40%)	30 ml	
Nitric acid/HF etches: These do not appear to be very sensitive to composition. HF should be 5–10%. Heating to 60–80 °C will accelerate etching, e.g. for Ti	(c) Nitric acid (1.40)	30–45 ml	Highly alloyed Ti, Hf, Zr; also Cr, W, Mo, V
	Hydrofluoric acid (40%)	10 ml	
	Water	60–45 ml	
Aqueous HCl HNO_3 etches. The reactivity can be reduced by adding water	(d) Hydrochloric acid (1.19)	66 ml	Gold, platinum, palladium. Used for cobalt alloy if added to 34 ml water
	Nitric acid (1.40)	34 ml	
Acidified hydrogen peroxide etch	(e) Hydrofluoric acid	10 ml	Dilute Ti, Hf and Zr alloys
	Hydrogen peroxide (30%)	45–60 ml	
	Water	45–30 ml	
Nitric acid in alcohol	(f) Nitric acid (1.40)	10 ml	Silver. (*Note*: for safety methanol must be used. It is dangerous to add more than 5% nitric acid to ethanol)
	Methanol	90 ml	
Hydrochloric acid etches	(g) Hydrochloric acid (1.19)	10 ml	Be and its alloys, especially for large grain sizes
	Water	90 ml	
	Ammonium chloride	4 g or 2 g	
	Picric acid	2 g	
	(h) Hydrochloric acid (1.19)	50 ml	Cobalt alloys
	Water	50 ml	
	60–80 °C for 30–60 min		

* Acids are concentrated, unless otherwise indicated, e.g. with specific gravity.

The most frequent novices' errors are to fail to remove completely the distorted metal beneath the original cut surface, to change the structure by overheating the specimen, to carry abrasives over (by lack of cleanliness) from a coarse stage of grinding or polishing to a finer one, and to develop false structures by staining through faulty drying after etching. Preparation of an unfamiliar material must be checked by repeated etching and repolishing to see that the structure remains constant as more metal is removed.

The early stages of preparation are common to most metals and types of specimen. Fine polishing may have to be varied to suit the metal. Etching is peculiar to the metal under examination and the feature of the structure to be investigated.

MOUNTING

Specimens of irregular shape, great fragility or very small size are best mounted in plastic. Several specimens, if of similar materials, may be prepared in the same mount, with a saving of time. For critical work a first-class finish is easiest to obtain on a rather small specimen, and this is best mounted for ease of handling except when electrolytic or chemical polishing is used. Edge-sections (e.g. sections through plated coatings) must almost inevitably be mounted.

The basic method is to place the specimen face-down in a die, cover it with plastic and apply the treatment needed to make the plastic set. The mount is conveniently 2–3 cm in dia. × approx. 1 cm high. Thermosetting, thermoplastic and cold-setting plastics are used. Very hard materials (especially tungsten wires) are sometimes mounted in low-melting-point glass. In many laboratories the majority of specimens are mounted.

It is essential to verify that the structure of the metal will not be materially affected by any heat and pressure applied in forming the mount. Some 'cold-setting' plastics become hot while setting.

Some plastics used, with their characteristics, are listed in Table 10.2.

Table 10.2 PLASTIC USED FOR MOUNTING

Plastics	*Type*	*Remarks*
Phenolic (e.g. 'Bakelite')	Thermosetting	Needs controlled heat and pressure. Sufficiently inert to most solvents. Normal grades good for general work but have high shrinkage; mineral-filled type (Bakelite × 262/2) preferable for edge-sections. If curing insufficient, e.g. too low a temperature, the mount is soft and is attacked by acetone
Polymethyl methacrylate (Perspex, Diakon)	Thermoplastic*	Needs controlled heat and pressure. Gives clear mount. Attacked by acetone. Rather soft
(NHP)	Warm-setting	Two-ingredient version. Polymer + catalyst + monomer. Can be used as casting resin, cold-setting resin with some pressure or warm-setting resin with pressure
Polyester (e.g. 'Marco' grade 26C)	Cold-setting	Several ingredients to be mixed for each batch, but gives good mounts without heat or pressure. Inert to usual solvents
Epoxy resins (e.g. Araldite)	Various	'Araldite' Grade D, a liquid casting resin, gives good mounts without heat or pressure. Inert to usual solvents
Phenolic varnish	Thermosetting liquid	For vacuum impregnation of oxide films, etc. (*see* text)
Polyvinyl chloride	Thermoplastic*	Low shrinkage. Inert to usual solvents but attacked by glacial acetic acid[2]
Diallyl phthalate (prepolymer)	Thermosetting	Needs controlled heat (130 140°C) and pressure. Low shrinkage good polishing characteristics[3]

* Must be cooled under pressure to low temperature to solidify before ejection.

Thermoplastics, such as polymethyl methacrylate, and thermosetting resins, such as 'Bakelite', are convenient for routine work because they are available as powders immediately ready for use, but they require a press, and normally only one size of cylindrical mount would be available. Cold-setting resins may be formed simply in a container consisting of a short piece of tube standing on a glass plate, and are therefore suitable for occasional use and odd shapes and sizes.

To examine a surface critically in section, support it if possible by plating (e.g. with copper or nickel) by applying an evaporated coating, or by wrapping with aluminium foil and mounting

under pressure (this method is useful for measuring the thickness of anodic or similar transparent films). Fragile oxide or other films may be held together by vacuum impregnation: use a vacuum desiccator and tap funnel to run resin varnish round the specimen in a rough vacuum (e.g. at about 10 torr residual pressure), remove the specimen and container to an oven (at 80 °C for Bakelite grade NPA) and heat until the resin is polymerized. A similar technique may be used with casting resins (if sufficiently fluid) which set without heat, although impregnation is liable to be less effective than with the very fluid hot varnish.

GRINDING

Emery or silicon-carbide cloths and papers are normally used. Silicon carbide is preferred because it is harder, has sharper particles and cuts at a faster rate. Use strips 20–30 cm × about 8 cm laid flat on plate glass, and rub the specimen to and fro on the strip. Start with not finer than 80 grit, and rub until all traces of saw cuts are removed. Turn the specimen through 90° and rub until the first set of emery scratches are removed. Repeat at least once, because the depth of the deformed layer is several times the depth of the residual scratches. Then progress to the next finer paper or cloth, turning the specimen through 90°, and again rub until the previous scratches are removed, then to the next finer paper similarly, until grade 600 silicon carbide paper is reached or, for softer alloys such as aluminium, the finest emery paper is reached (usually grade 4/0, but grade 6/0 is sometimes useful). A fine paraffin oil (e.g. 'white spirit') should be flooded over the papers to act as a lubricant, or they should be continuously washed with water or white spirit. For soft metals, a more viscous liquid paraffin is preferred to avoid pick-up of silicon carbide or emery in the surface of the specimen. Slowly rotating silicon carbide discs continuously washed with water are frequently used.

For very hard metals diamond hones[4] and laps[106] have been used for grinding.

Metals containing constituents of widely differing hardness may develop undesirable relief when ground on fine papers. An alternative is to use a lead lap. Lead foil is stretched over a glass plate and is flooded with white spirit. Fine abrasive (e.g. alumina) is worked into the surface by placing some on the wet surface and working it in with a steel disc. Any loose abrasive remaining is washed off, and, in use, the plate carrying the lap is mounted at a slight tilt in a dish and the surface is washed continuously with a slow stream of white spirit to remove loose particles.

MECHANICAL POLISHING

Mechanical polishing is often done in two stages, with a coarse and a fine abrasive or polishing agent, respectively. The coarse polishing stage is carried out at 300 r.p.m., uses a low nap or napless cloth such as Selvyt or synthetic cloth. (The nap is intended to retain the abrasive without causing relief effects.) It is fed with a suspension of a relatively coarse abrasive. The final polishing stage is carried out with finer abrasive at a lower rotational speed (100 r.p.m.) using medium nap cloth, preferably dense electroflocked terylene fibres bonded to a chemically resistant backing. Polishing agents include α-alumina, γ-alumina, magnesium oxide, chromium oxide, proprietary metal polishes and diamond dust. The polishing agent may have a cutting action or it may produce a 'flowed' layer on the surface or both. The modern tendency is to use cutting, rather than flowing, polishing agents, and diamond dust is now preferred. α-Alumina (a fast-cutting hard material) may be made by roasting aluminium sulphate to 1400 °C (a high proportion of α is obtained at 1200 °C) and can be used without further treatment. γ-Alumina suitable for fine polishing may be made by heating to 950 °C. Suitable magnesium oxide is obtainable cheaply from medical suppliers. Magnesium oxide is slowly converted to carbonate when damp, so polishing cloths, if kept overnight, are cleaned with dilute acid and thoroughly washed. Diamond powder of up to 12 μm diameter is used for rough polishing and 0–1 or 0–$\frac{1}{2}$ μm diameter for fine polishing (usually to be followed briefly with γ-alumina, as it leaves very fine scratches). The powder may simply be rubbed into cloth which is kept lubricated with white spirit (a plastic rim pressed on to the polishing wheel conserves the powder), or may be made into a cream. The recipe below[5] is recommended:

The ingredients are:

Stearic acid	12.5 g
Triethanolamine	6 ml
Water	25 ml
Diamond powder	0.5 g

The stearic acid is melted and heated to 80–90 °C. The triethanolamine and most of the water are mixed and heated to the same temperature range, a small amount of wetting agent and the diamond powder are added, and the abrasive is shaken into uniform suspension. The molten stearic acid is stirred vigorously with a mechanical stirrer and the abrasive suspension is introduced rapidly. The water not used in the original suspension can be used to wash in any abrasive remaining in the container. Continue stirring until the emulsion cools and thickens.

Where it is particularly required to avoid relief effects in specimens containing constituents of widely differing hardness, diamond dust may be used on a pile-free nylon or terylene cloth.

Some metals are readily stained or corroded in the presence of water, and for these a non-aqueous polishing mixture, normally diamond with white spirit, is preferred. In borderline cases the use of distilled water, rather than tap water, helps to avoid staining.

After polishing by any method, the specimen must be thoroughly washed and dried as described under *Etching* (p. **10**–16), or washed and etched immediately. The specimen should be flooded with water, then with alcohol or acetone to remove all water and finally dried with a blast of hot air. If the polish or etch is non-aqueous, wash with alcohol or acetone.

Polish attack is a method of hastening polishing by the simultaneous use of an etching agent. For instance, ammonia is used with advantage on the pad in polishing copper alloys. The action is thought to depend on the enhanced chemical activity of the 'flowed' layer.

Attack polishing in a deep layer of liquid is done by mounting a polythene pot on the spindle of the polishing machine, with the polishing pad in it and submerged in the liquid.[6] Table 10.3 gives reagents for use with various metals by this method. Several solutions have also been proposed for magnesium alloys.[7]

Table 10.3 ATTACK POLISHING CONDITIONS FOR VARIOUS METALS AND ALLOYS USING TERYLENE-COVERED LAPS[6]

Material	*Solution**		*Time* min	*Remarks*
Uranium	CrO_3	50 g	20–30	Medium contrast under polarized light, no pitting, good resistance to oxidation
	H_2O	100 ml		
	HNO_3 (1.40)	10 ml		
Zirconium	HNO_3 (1.40)	50 ml	1–10	Good contrast under polarized light. Slight grain relief
	Glycerol	150 ml		
Bismuth	HNO_3 (1.40)	50 ml	3–5	Good contrast under polarized light. Requires less pressure than usual
	Glycerol	150 ml		
Chromium	$(COOH)_2$	15 g	5–10	Bright polish revealing oxides, etc.
	H_2O	150 cm		
Molybdenum and tungsten	Pot. ferricyanide	3.5 g		
	Sodium hydroxide	1 g		
	Water	300 ml		

* Acids are concentrated, unless otherwise indicated, e.g. with specific gravity.

ELECTROLYTIC POLISHING

Very full reviews have been given by Jacquet,[8] Tegart,[9] and Petzow[1] which may be consulted for individual references. A comparison with mechanical methods has been made by Samuels.[10]

The specimen is made with the anode in a suitable solution, and conditions are adjusted so that the hills on the surface are dissolved much more rapidly than the valleys, and when enough metal has been removed a smooth surface is obtained. The condition for polishing often corresponds to a nearly flat (i.e. constant current) region in the curve for cell current versus voltage. As the voltage is increased (*see* Figure 10.1), etching (AB) is replaced by film formation (BC). The voltage then increases and the current falls slightly as the film disappears and polishing conditions are established (CD). At higher voltages, gas evolution occurs with pitting. Near E gas evolution is rapid and polishing continues but the region just below D is preferred. By reducing the voltage to

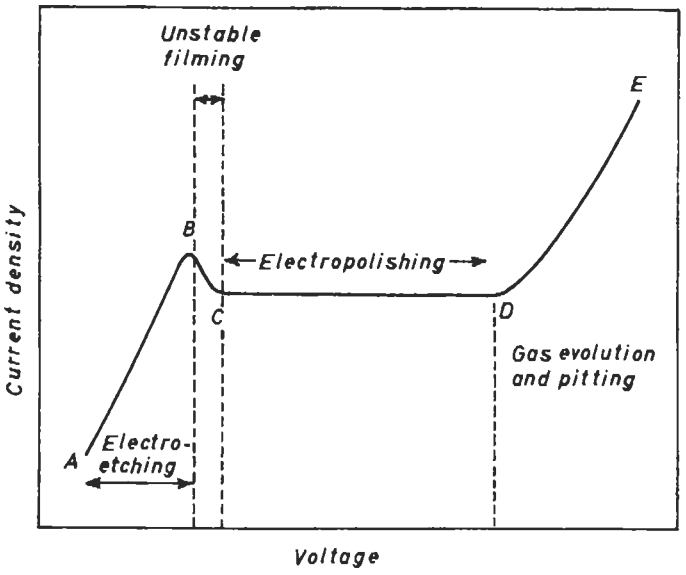


Figure 10.1 *Idealized relationship between current density and voltage in electropolishing cell.*

below B, the specimen can be etched in the same operation. For many specimens electropolishing leads to a great saving in time, and it reliably produces surfaces free from strain provided sufficient metal is removed in the process. It tends to exaggerate porosity and is unsuitable for highly porous specimens. Inclusions are often removed, though not invariably, and their place taken by severe pits. Many two-phase and complex alloys, however, can be successfully polished.

Apparatus. To cover the widest range of applications a d.c. supply of 4–5 A at voltages variable up to at least 60 V is required, but some solutions require only 2 V. Accurate voltage regulation is essential, and a rectifier set fed from a variac, a tapped battery or a potentiometer circuit across a constant d.c. source is recommended. Published recommendations for particular solutions sometimes state the voltage, and sometimes the current density, required. It is preferable to work on voltage, as the current density for a given electrode condition is much affected by temperature and other variables. If both are stated, but cannot be simultaneously obtained, the solution is probably wrong; if it is not, the current density should be disregarded. Two general cell arrangements are used: with electrodes in a beaker of still or gently stirred solution, and with flowing or pumped electrolyte.[11–13] The first arrangement is easily set up and often suffices; the second is more powerful but requires more complicated apparatus (obtainable commercially, however). The characteristics are quite different: with flowing electrolyte a good polish may be obtained with more strongly conducting solutions, and hence with higher current densities, and it is therefore frequently possible to remove more metal in polishing and to start with a more roughly prepared surface. A small area of an article may be electropolished by the use of electrolyte flowing from a vertical jet above the article, the jet itself containing a projecting wire to act as cathode.[13] In suitable conditions, polishing of an area already rubbed with emery may be completed in 3–10 s. Apparatus for this method is also available commercially.

Jacquet has described a device (the 'Ellapol') in which an electrolyte is applied to the surface by a small swab surrounding the cathode. The device can conveniently be used to polish a small area of a large component *in situ* (*see* e.g., refs. 14–16).

Solutions for electropolishing particular metals are listed in Table 10.4. Table 10.4 is not a complete list, but should cover most requirements. More detailed solutions are given in refs. 1, 2, 8 and 9. Minor differences between solutions are often a consequence of the cell used. The most widely useful solutions are methyl alcohol–nitric acid mixtures, strong solutions of phosphoric acid and mixtures of perchloric acid with alcohol, acetic acid or acetic anhydride. Mixtures of perchloric acid with acetic anhydride, although frequently the best polishing agents, are often explosive and deserve respect. They must be kept cold in use; plastics (especially cellulose) and bismuth must be kept away from them, and they must not be stored in the laboratory as they are liable to explode without apparent reason. The explosion of a few hundred millilitres is not likely

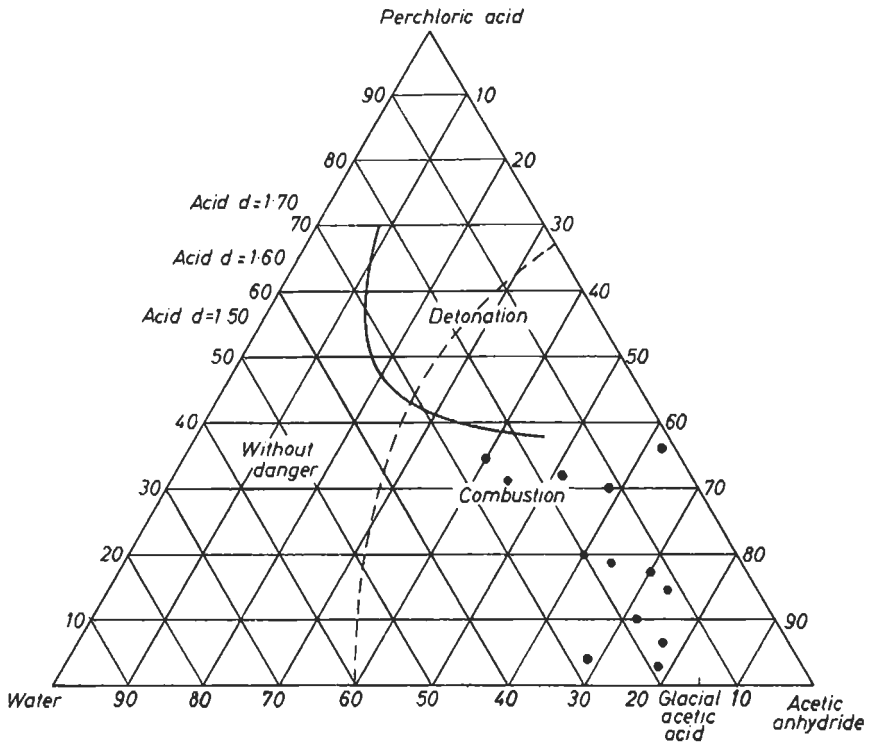


Figure 10.2 *Characteristics of perchloric acid/acetic anhydride/water solutions (after Jacquet[8, 17] and Petzow[1]).*
● = *Typical electrolytes*

to do great physical damage, but larger quantities should not be used. The limits of the dangerous mixtures, according to Jacquet, the originator,[8, 17] are indicated in Figure 10.2. Perchloric acid must always be added to the acetic anhydride–water mixture to avoid compositions in the detonation zone.

Table 10.4a ELECTROLYTIC POLISHING SOLUTIONS FOR VARIOUS METALS AND ALLOYS

Because of the considerable number of solutions published in the literature, a selection has been made on the basis of (a) wide usage, (b) simplicity of composition, and (c) least danger. References 1 and 2 provide a wider range of compositions. Temperatures should be in the range 15–35°C. Cooling should be used to avoid temperatures above 35°C unless stated otherwise.

	Composition of solution		*Usage*	*Cell voltage*	*Time*	*Cathode*
1	Ethanol	800 ml	Al alloys (not Al–Si)	30–80	15–60 s	Stainless steel
	Distilled water	14 ml	Most steels	35–65	15–60 s	Stainless steel
	Perchloric acid (1.61)	60 ml	Lead alloys	10–35	15–60 s	Stainless steel
			Zinc alloys	20–60	15–60 s	Stainless steel
			Magnesium alloys	20–40	up to 2 min	Nickel
2	Ethanol	800 ml	Al alloys	35–80	15–60 s	Stainless steel
	Perchloric acid (1.61)	200 ml	Stainless steels	35–80	15–60 s	Stainless steel
			Pb alloys	15–35	15–60 s	Stainless steel
			Zn alloys	20–60	15–60 s	Stainless steel
			and many other metals			
3	Ethanol	940 ml	Stainless steel	30–45	15–60 s	Stainless steel
	Distilled water	6 ml	Thorium	30–40	15–60 s	Stainless steel
	Perchloric acid (1.61)	54 ml				

Table 10.4(a) ELECTROLYTIC POLISHING SOLUTIONS FOR VARIOUS METALS AND ALLOYS—*continued*

Composition of solution		*Usage*	*Cell voltage*	*Time*	*Cathode*
4 Ethanol	700 ml	Al alloy	30–65	15–60 s	Stainless steel
Water	120 ml	Steel, cast iron			
2-Butoxyethanol	100 ml	Ni, Sn, Ag, Be			
Perchloric acid (1.61)	80 ml	Ti, Zr, U, Pb			
Glycerol (100 ml) can replace butoxyethanol		Complex steels and nickel alloy general use			
5 Ethanol	760 ml	Al alloys	30–60	15–60 s	Stainless steel
Distilled water	30 ml	including Al–Si alloys			
Ether	190 ml	Fe–Si alloys Sb			
Perchloric acid (1.61)	20 ml	Preferred solution for Al alloys			
6 Methanol	590 ml	Germanium and silicon	25–35	30–60 s	Stainless steel
Water (distilled)	6 ml	Titanium	~60	45 s	Stainless steel
2-Butoxyethanol	350 ml	Vanadium	~30	3–5 s*	Stainless steel
Perchloric acid	54 ml	Zirconium	~70	15 s	Stainless steel
7 Glacial acetic acid	940 ml	Cr, Ti, U, Zr, Fe	20–60	up to 5 min	Stainless steel
Perchloric acid (1.61)	60 ml	Cast iron, all steels, V			
		Re and many other metals			
8 Glacial acetic acid	900 ml	Ti, Zr, U steels	10–60	up to 2 min	Stainless steel
Perchloric acid (1.61)	100 ml	Superalloys			
9 Glacial acetic acid	800 ml	U, Ti, Zr, Al steels	40–100	up to 15 min	Stainless steel
Perchloric acid (1.61)	200 ml	Superalloys			
10 Glacial acetic acid	700 ml	Nickel, Pb,	40–100	up to 5 min	Stainless steel
Perchloric acid (1.61)	300 ml	especially Pb–Sb alloys			
11 Phosphoric acid (1.75)		Cobalt, Fe–Si alloys	1–2	up to 5 min	Stainless steel
12 Distilled water	300 ml	Cu, Cu alloys (not Cu–Sn)	1–1.6	10–40 min	Copper
Phosphoric acid (1.75)	700 ml	Stainless steels—rinse in 20% H_3PO_4			
13 Distilled water	600 ml	Brasses, Cu–Fe, Cu–Co	1–2	up to 15 min	Copper or stainless steel
Phosphoric acid	400 ml	Co, Cd			
14 Distilled water	200 ml	Al, Mg, Ag	25–30 at 40 °C	4–6 min	Aluminium
Ethanol	400 ml				
Phosphoric acid (1.75)	400 ml				
15 Ethanol	300 ml	U (preferred solution)	20–30	4–6 min	Aluminium
Glycerol	300 ml				
Phosphoric acid (1.75)	300 ml				
16 Ethanol	500 ml	Mn, Mn–Cu	18	up to 10 min	Stainless steel
Glycerol	250 ml				
Phosphoric acid (1.75)	250 ml				
17 Ethanol	625 ml	Mg, Zn alloy	1.5–2.5	up to 30 min	Stainless steel
Phosphoric acid (1.75)	375 ml				
18 Ethanol	445 ml	U alloys	18–20	up to 15 min	Stainless steel
Ethylene glycol	275 ml				
Phosphoric acid (1.75)	275 ml				
19 Distilled water	750 ml	Stainless steel	1.5–6.0	up to 10 min	Stainless steel
Sulphuric acid (1.75)	250 ml	iron, nickel			
		Molybdenum	1.5–6.0	1 min	Stainless steel
20 Methanol	875 ml	Molybdenum	6–18	1 min	Stainless steel
Sulphuric acid (1.84)	125 ml		Keep below 27 °C		

*With vanadium, give several 3–5 s bursts and avoid heating.

Table 10.4(a) ELECTROLYTIC POLISHING SOLUTIONS FOR VARIOUS METALS AND ALLOYS—*continued*

Composition of solution		*Usage*	*Cell voltage*	*Time*	*Cathode*
21 Distilled water	830 ml	Zn, Al bronze	1.5–12	up to 1 min	Stainless steel
Chromium trioxide	170 g	Brass			
22 Distilled water	450 ml	Tin			
Phosphoric acid (1.75)	390 ml	Tin bronzes (high tin)	2	up to 15 min	Copper
Sulphuric acid (1.84)	160 ml	(rinse in 20% H_3PO_4)			
23 Distilled water	330 ml	Tin			
Phosphoric acid (1.75)	580 ml	Tin bronzes (low	2	up to 15 min	Copper
Sulphuric acid (1.84)	90 ml	tin <6%)			
		(rinse in 20% H_3PO_4)			
24 Distilled water	170 ml	Stainless steel	2	up to 60 min	Stainless steel
Chromium trioxide	105 g	(use at 35–40 °C)			
Phosphoric acid (1.75)	460 ml				
Sulphuric acid (1.84)	390 ml				
25 Distilled water	240 ml	Stainless steel	2	up to 60 min	Stainless steel
Chromium trioxide	80 g	Alloy steels			
Phosphoric acid (1.75)	650 ml	(use at 40–50 °C)			
Sulphuric acid (1.84)	130 ml				
26 Hydrofluoric acid (40%)	100 ml	Tantalum		5–15 min	Graphite
Sulphuric acid (1.84)	900 ml	Niobium			
		(use at ~40 °C)			
27 Glycerol	750 ml	Bismuth	12	1–5 min	Stainless steel
Glacial acetic acid	125 ml				
Nitric acid (1.40)	125 ml				
(*Warning:* This solution will decompose vigorous if kept, especially if cathode left in it. Throw away solution as soon at finished with)					
28 Methanol	685 ml	Molybdenum	19–35	30 s	Stainless steel
Hydrochloric acid (1.19)	225 ml				
Sulphuric acid (1.84)	90 ml				
Keep cool below 2 °C. Avoid water contamination.					
29 Ethanol	885 ml	Ti and most other	25–50	5 min	Stainless steel
n-Butyl alcohol	100 ml	alloys			
Hydrated aluminium trichloride	109 g				
Anhydrous Zn chloride	250 g				
30 The above diluted with 120 ml distilled water		Zinc	20–40	up to 3 min	Stainless steel
31 Glycerol	870 ml	Zirconium	9–12	up to 10 min	Stainless steel
Hydrofluoric acid (40%)	43 ml				
Nitric acid (1.40)	87 ml				
As 27—will decompose on standing and must be thrown away as soon as possible					
32 Potassium cyanide	80 g	Gold, silver	7–5	2–4 min	Graphite
Potassium carbonate	40 g				
Gold chloride	50 g				
Distilled water to 1000 ml					
33 Sodium cyanide	100 g	Silver	2–5	up to 1 min	Graphite
Potassium ferrocyanide	100 g				
Distilled water to 1000 ml					

Table 10.4(a) ELECTROLYTIC POLISHING SOLUTIONS FOR VARIOUS METALS AND ALLOYS—*continued*

Composition of solution		*Usage*	*Cell voltage*	*Time*	*Cathode*
34 Sodium hydroxide	100 g	Tungsten lead	6	10 min	Graphite
Distilled water to 1 000 ml					
35 Methanol	600 ml				
Nitric acid (1.40)	330 ml	Ni, Cu, Zn, Ni–Cu Cu–Zn, Ni–Cr	40–70	10–60 s	Stainless steel
Warning: Do not keep longer than necessary. May become explosive. On no account substitute ethanol for methanol		Stainless steel, In, Co Very versatile			

Table 10.4(b) RECOMMENDED ELECTROPOLISHING SOLUTION FROM TABLE 10.4(a) FOR SPECIFIC METALS AND ALLOYS

Alloy	*Electrolyte* (No. in Table 10.4(a))
Aluminium	1, 2, 4, 9, 14
Aluminium–silicon	5
Antimony	5
Beryllium	4
Bismuth	27
Cadmium	13
Cast iron	4, 7
Chromium	7
Cobalt	11, 13, 35
Copper and alloys	12, 13, 35
Copper–tin alloys	22, 23
Copper–zinc alloys	13, 21
Germanium	6
Gold	32
Hafnium	4
Indium	35
Iron-base alloys	4, 7, 8, 9, 19
Lead	1, 2, 4, 10, 34
Magnesium	1, 14, 17
Manganese	16
Molybdenum	19, 20, 28
Nickel and superalloys	4, 8, 9, 10, 19, 35
Niobium	26
Rhenium	7
Silver	4, 14, 32, 33
Stainless steels	1, 2, 3, 4, 7, 8, 9, 12, 19, 24, 25, 35
Steels: carbon and alloy	1, 4, 7, 8, 9, 19, 25
Tantalum	26
Thorium	3
Tin	4, 22, 23
Titanium	4, 6, 7, 8, 9, 29
Tungsten	34
Uranium	4, 7, 8, 9, 15, 17
Vanadium	6, 7
Zinc	1, 2, 17, 21, 30, 35
Zirconium	4, 6, 7, 8, 9, 31

CHEMICAL POLISHING

Chemical polishing is usually adopted as a quick method of obtaining a passable result, rather than as a method of preparing a perfect surface. However, where it is difficult to prepare a

work-free surface by other means, as with some very soft metals or where other difficulties are encountered, it may provide the best method of preliminary or final preparation.

In general, a ground or turned specimen is held in the polishing agent until a polish is obtained, and it is then etched or washed and dried, as appropriate. Reagents are listed in Table 10.5.

Table 10.5 REAGENTS FOR CHEMICAL POLISHING[1,2,9]

Metal	*Reagent**		*Time*	*Temperature* °C	*Remarks*
Aluminium and alloys	Sulphuric acid (1.84) Orthophosphoric acid Nitric acid	25 ml 70 ml 5 ml	30 s–2 min	85	Very useful for studying alloys containing intermetallic compounds, e.g. Al–Cu, Al–Fe and Al–Si alloys
Beryllium	Sulphuric acid (1.84) Orthophosphoric acid (1.75) Chromic acid Water	1 ml 14 ml 20 g 100 ml	Several min	49–50	Rate of metal removal is approx. 1 $\mu m\,min^{-1}$. Passive film formed may be removed by immersion for 15–30 s in 10% sulphuric acid
Cadmium	Nitric acid (1.4) Water	75 ml 25 ml	5–10 s	20	Cycles of dipping for a few seconds, followed immediately by washing in a rapid stream of water are used until a bright surface is obtained
Copper	Nitric acid Orthophosphoric acid Glacial acetic acid	33 ml 33 ml 33 ml	1–2 min	60–70	Finish is better when copper oxide is absent
Copper alloys	Nitric acid Hydrochloric acid Orthophosphoric acid Glacial acetic acid	30 ml 10 ml 10 ml 50 ml	1–2 min	70–80	Specimen should be agitated
Copper–zinc alloys	Nitric acid (1.40) Water	80 ml 20 ml	5 s	40	Use periods of 5 s immersion followed immediately by washing in a rapid stream of water. Slight variations in composition are needed for α–β and β–γ brasses to prevent differential attack. With β–γ alloys, a dull film forms and this can be removed by immersion in a saturated solution of chromic acid in fuming nitric acid for a few seconds followed by washing
Germanium	Hydrofluoric acid Nitric acid Glacial acetic acid	15 ml 25 ml 15 ml 3–4 drops	5–10 s	20	—
Hafnium	Nitric acid Water Hydrofluoric acid	45 ml 45 ml 8–10 ml	5–10 s	20	As for zirconium
Iron	Nitric acid Hydrofluoric acid (40%) Water	3 ml 7 ml 30 ml	2–3 min	60–70	Dense brown viscous layer forms on surface; layer is soluble in solution. Low carbon steels can also be polished, but the cementite is attacked preferentially
Irons and steels	Distilled water Oxalic acid ($100\,g\,l^{-1}$) Hydrogen peroxide (30%)	80 ml 28 ml 4 ml	15 min	35	The solution must be prepared freshly before use. Careful washing is necessary before treatment. A microstructure is obtained similar to that produced by mechanical polishing, followed by etching with Nital

* Acids are concentrated, unless otherwise indicated.

Table 10.5 REAGENTS FOR CHEMICAL POLISHING—*continued*

Metal	*Reagent**		*Time*	*Temperature* °C	*Remarks*
Lead	Hydrogen peroxide (30%) Glacial acetic acid	80 ml 80 ml	Periods of 5–10 s	20	Use Russell's reagent (Table 10.1) to check that any flowed layer has been removed before final polishing in this reagent
Magnesium	Fuming nitric acid Water	75 ml 25 ml	Periods of 3 s	20	The reaction reaches almost explosive violence after about a minute, but if allowed to continue it ceases after several minutes, leaving a polished surface ready for examination. Specimen should be washed immediately after removal from solution
Nickel	Nitric acid (1.40) Sulphuric acid (1.84) Orthophosphoric acid (1.70) Glacial acetic acid	30 ml 10 ml 10 ml 50 ml	½–1 min	85–95	This solution gives a very good polish
Silicon	Nitric acid (1.40) Hydrofluoric acid (40%)	20 ml 5 ml	5–10 s	20	1:1 mixture also used
Tantalum	Sulphuric acid (1.84) Nitric acid (1.40) Hydrofluoric acid (40%)	50 ml 20 ml 20 ml	5–10 s	20	Solution is useful for preparing surfaces prior to anodizing
Titanium	Hydrofluoric acid (40%) Hydrogen peroxide (30%) Water	10 ml 60 ml 30 ml	30–60 s	—	Swab till satisfactory
	Hydrofluoric acid (40%) Nitric acid (1.40) Lactic acid (90%)	10 ml 10 ml 30 ml			Few seconds to several minutes according to alloy
Zinc	Fuming nitric acid Water	75 ml 25 ml	5–10 s	20	As for cadmium
	Chromium trioxide Sodium sulphate Nitric acid (1.40) Water to 100 ml	20 g 1.5 g 5 ml	3 min – 30 min	20	Solution must be replaced frequently
Zirconium (also Hafnium)	Acid ammonium fluoride Nitric acid (1.40) Fluosilicic acid Water	10 g 40 ml 20 ml 100 ml	½–1 min	30–40	Rate of dissolution varies markedly with temperature and is about 20–60 μm min^{-1} in the given range
	Nitric acid (1.40) Water Hydrofluoric acid (40%)	40–45 ml 40–45 ml 10–15 ml	5–10 s repeated	—	Reaction is vigorous at air/solution interface, and specimen is therefore held near surface of liquid. Hydrogen peroxide (30%) can be used in place of water.

* Acids are concentrated, unless otherwise indicated.

ETCHING

Specimens should first be examined without etching. This reveals features which have a significant difference in reflectivity from the main structure, such as differences in colour and relief due to phases of large difference in hardness. Non-metallic inclusions, cracks, porosity and various kinds of pit can be recognized clearly and should be recorded because subsequent etching treatments can change both shapes and colours.

In order to obtain the maximum resolution from the optical microscope with minimum reflections from stray light, the microscope must be set up using the 'Köhler' principle of illumination.[25] Most modern microscopes are constructed to achieve this principle and it is only necessary to adjust the two iris diaphragms. The first of these, usually called the field diaphragm, should project an image sharply in focus on the specimen and should be adjusted so that the image falls just outside the field of view. The aperture diaphragm should be sharply in focus on the rear of the objective lens. It can be viewed by removing the eyepiece and should be adjusted (through an auxiliary lens on some microscopes) so that the image is centrally located on the rear of the objective and it illuminates 90% of the lens area. If after these adjustments the image is too bright, it should be dimmed by either reducing the light intensity or interposing a filter. Reduction of the aperture reduces the resolution achieved by the lens, emphasizes differences in level and can introduce artefacts.

To emphasize small differences in surface topography, several techniques are available which are usually provided on good optical microscopes. These include:

1. Dark field illumination[2,26]

By this technique a specimen is illuminated by an annulus of light which passes up the outside of the objective and is focussed as a cone by a concave reflector. Thus the normal beam of light is not used to form the image. Instead, the light scattered by angled surfaces is focused to make the image and thus the contrast is reversed. Cracks, inclusions and defects are seen as bright features on a black background.

2. Phase contrast

This technique converts differences in surface height (which produce differences in phase) into differences in intensity which the eye can detect more readily. To achieve this, an annular disc is placed at the front focal plane of the condenser lens of the microscope. This is then imaged at the back focal plane of the objective where is placed a transparent phase retarding ring of the same shape and size as the image of the annulus. The light passing through the ring is retarded (or it can be advanced) by one quarter of the wavelength of the monochromatic light used. The diffracted light from the specimen passes outside this ring and is not retarded (or advanced) and the image formed as light and dark contrast. The low areas appear dark and the high areas light for phase retardation (or the opposite for phase advancement). This technique is sensitive to surface changes of approx. 5 nm.

3. Interference microscopy[27–30]

Interference microscopes have been described by several authors but the most sensitive and useful techniques have been developed by Tolansky[27]. His multiple beam interferometry can be used with conventional microscopes at magnifications of up to about 250. Monochromatic light is essential and a parallel beam normal to the surface is used. An optical flat, silvered or aluminized to give about 95% reflectivity, is placed in contact with the specimen and is slightly tilted to produce a thin wedge between the two. The light is repeatedly reflected between the specimen and the optical flat, and interference takes place to produce very thin, sharp, dark fringes. The spacing can be varied by the tilt of the plate. Where a change in the surface of the specimen occurs, e.g. a step or depression, the light path occurs and the interference fringe is displaced one way or the other. A total fringe displacement corresponds to a change in height of half the wavelength of light used and so it is possible to measure surface displacements of about 5–50 nm. To obtain sharp fringes, the reflectivity of the metallic surface should be the same as the reference plate, i.e. approximately 95%, and it may be necessary to aluminize the specimen surface for the best results.

Normarski has designed a very sensitive microscope for detecting steps in the surface of a specimen.[26,30] He uses a conventional polarizing microscope, into which a double quartz prism is inserted between the objective and the analyser. If a step is present, this produces two images slightly displaced to one another and interference between these produces light and dark fringes, the spacing of which can be varied by adjusting the prism. A modification of the technique produces interference contrast in images similar to those produced by phase contrast. This is often called DIC –differential interference contrast.[146]

4. Polarized light

The use of polarized light is an extremely powerful method of studying inclusions and structures of unetched and electropolished surfaces.

The equipment needed includes a monochromatic source of illumination, a polarizer (Nicol prism or polaroid filter) which can be rotated to change the plane of polarization, and an analyser of comparable material which can also be rotated. When the analyser is oriented so that its plane of polarization is at 90° to that of the polarizer, an isotropic specimen will appear black if the objectives and the microscope are well adjusted and no depolarization occurs. The objectives should be strain free for the highest sensitivity.

Bausch and Lomb use a Foster prism,[25] which produces the effect of 'crossed polars' with isotropic materials. A rotatable quarter wave plate is added so that the effect of rotating the analyser towards the parallel position can be achieved.

With isotropic metals and the polarizer and analyser set in the 'crossed' position, no light reaches the eyepiece. However, with an optically anisotropic material, e.g. a hexagonal metal like beryllium, magnesium or zinc, the reflected beam becomes elliptically polarized and the intensity of the component normal to the plane of polarization of the incident light depends on the orientation of the anisotropic structure. Thus the intensity of light which passes through the analyser will be dependent on the orientation of the structure to the surface of the specimen and to the incident beam. The image will vary from dark to bright, according to orientation and the grain structure of an anisotropic material will be revealed. On rotating the specimen, the intensity of light passing through the analyser from any one grain will pass from minimum to maximum intensity every 45° to give four maxima per revolution at 90° to each other, with a minimum intensity at 45° to each maximum. If the analyser and polarizer are not quite crossed and differ by a few degrees, only two maxima and minima occur. The difference in contrast between the maxima and minima is much greater under these conditions and improves the sensitivity of the method, especially for weakly anisotropic or pleochroic materials.

The method can be used for studying grain structures, twins and martensites. In uranium alloys, for instance, the isotropic gamma phase can be distinguished from weakly anisotropic retained beta phase and the strongly anisotropic variants of the alpha phase. Martensites can be distinguished from retained beta phase in copper base alloys. In other systems, such as aluminium, grain structure can be revealed by anodizing to produce an anisotropic oxide film which has orientation related to the underlying lattice.

The other useful application is in the identification of inclusions. Glassy inclusions such as silicates display the so-called 'optical cross'. Others are optically anisotropic, e.g. MnO and MnS can be distinguished in steels. Other inclusions are pleochroic and display characteristic colours under crossed polars. Examples are the grey Cu_2O phase in copper alloys which is blood red under polarized light, and Cr_2O_3 which changes from blue grey to a beautiful emerald green. References 26, 41, 44 and 146 should be consulted for more detail.

The anisotropic metals include:

Antimony	Tin
Beryllium	Titanium
Cadmium	Uranium
Hafnium	Zinc
Magnesium	Zirconium

If correctly prepared, these metals will reveal their structure under crossed polars.

The following metals can be made to respond to polarized light by anodizing to produce an anisotropic film, or by deep etching to produce an uneven surface with etch pits.[44]

Aluminium	Molybdenum
Chromium	Nickel
Copper	Tungsten
Iron	Vanadium
Manganese	

5. Colour (based mainly on ref. 44 and 146)

Only two metals demonstrate natural colour: gold and copper.

Others can be rendered coloured by:

(*a*) Optical methods such as polarized light, especially of etched structures with a sensitive tint plate inserted between polarizer and analyser. This is used on Bausch and Lomb microscopes and converts shades of grey into shades of blue and magenta. Brighter colours are obtained in etched structures. All these methods change shades of grey to colour contrast.

(*b*) By producing interference films by heat tinting or by chemical processes. This can colour phases according to their reactivity or grains according to their orientation. Most frequently, the reagents used leave thin films of oxide, sulphide, chromate, phosphate or molybdate which cause colouration by interference of light. The colour depends on the thickness of films. This method is most appropriate for distinguishing inclusions or intermetallic compounds. The more useful applications are given in Tables 10.6 to 10.8. More details and illustrations are given in ref. 44.

6. Physical methods

(*a*) *Cathodic vacuum etching* (*ion etching*). The specimen is made a cathode in a high voltage gas discharge. High energy ions such as argon are accelerated at voltages of 1–10 kV and gas pressures of 10 μm. This bombardment removes atoms at a rate dependent on orientation, presence of grain boundaries, intermetallic compounds.

(*b*) *Thermal etching*. On heating specimens, e.g. in vacuum or inert atmosphere, atoms are lost from regions of low binding energy, e.g. grain boundaries. Surface tension forces lead to changes in surface topography at grain boundaries, leaving a structure characteristic of the high temperature.

7. Chemical and electrochemical etching

Etching is usually an oxidation process. In general, elements with electrode potentials more negative than hydrogen will pass into solution in many solutions, the rate depending on the local environment, so resulting in grain boundary attack or outlining of phases or other structures. For elements with electrode potentials more positive than hydrogen, or for elements which polarize, solutions containing oxidizing agents are needed. Making the specimen the anode in a low voltage cell has the same effect. Indeed, most electropolishing solutions will cause etching if the voltage is reduced, usually by a factor of 10.

Detailed etching procedures for individual metals are given below but, as a general principle, iron alloys are usually etched in dilute oxidizing agents, e.g. nitric acid or picric acid in alcohol. Stainless steels are usually etched in weak oxidizing reagents in alkaline solution, e.g. alkaline ferricyanides. Virtually the same result is achieved electrolytically in a 1% potassium hydroxide solution. While claims are made by many authors that subtle selective etches can be produced by minor changes in composition of the etching solution, these are often difficult to achieve and reproduce and need considerable skill and experience by the metallographer to achieve.

In the case of copper alloys, most etchants require an ammoniacal atmosphere plus an oxidizing reagent such as air (by swabbing), hydrogen peroxide or dichromates, permanganates, persulphates, etc. Electrolytic etching in an oxidizing acid, e.g. 1% chromium trioxide often suffices, the control of etching being achieved by varying the voltage.

Many pure metals are notoriously difficult to etch, e.g. aluminium. If there are no natural impurities present to induce grain boundary attack, etchants should be used which can chemically deposit elements which can be reduced and diffuse into the boundaries, e.g. gallium from a gallium salt solution.

Reduction reactions can also be used and these cause staining or colouration of phases, especially intermetallic compounds.

A wide variety of etching reagents has been devised by empirical methods. Some of these are reproduced but the perceptive reader will see that these can be modified easily to cope with new compositions. Small amounts of some components are needed to control pH or potential. Some solutions are not stable and their effectiveness will change with time. Others containing mixtures of oxidizing agents and organic chemicals can become very dangerous with time and should only be retained for short times and be discarded immediately after use.

Reference is given to simple electrolytic etches and it is recommended that these be used with a potentiostat[18,19] to control the potential at a known and reproducible value. This will aid reliable and consistent etching.[20,21,22]

8. Washing and drying

On completion of etching (with most etches) the specimen should at once be flooded with water, washed free from water with acetone or alcohol (avoid ether) and dried in a blast of hot air from a hair dryer or equivalent. With non aqueous etches it is often preferable to do the initial washing with alcohol or acetone rather than water.

Porous specimens are often easily stained by residual etching solution seeping out of the pores. This trouble can usually be avoided by prolonging the washing and drying stages, and in severe cases by prolonged soaking of the specimen in alcohol or acetone before final drying. If this fails the specimen may be treated with a clear lacquer immediately after drying.

Table 10.6 COLOUR ETCHES FOR STEEL

Reagent		*Procedure*	*Comments*
1 Saturated sodium thiosulphate	50 ml	Immersion for times dependent on stainless steel	ϵ martensite–white α martensite–black Austenite–grey
Potassium metabisulphate	5 g		
2 20% HCl in water	100 ml	Immersion for 5–10 s	Carbon and tool steels Martensite–blue Bainite–red Carbides–white
Ammonium bifluoride	2 g		
Potassium metabisulphite	1 g		
3 As above		As above	Stainless steels Martensite–blue

Table 10.7 COLOUR ETCHES FOR CAST IRON

Reagent		*Procedure*	*Comments*
1 HCl (35%)	2 ml	5–6 min immersion	Fe_3C–red/violet
Selenic acid	0.5 ml	2–3 min if pre-etched	Ferrite–white
Ethanol	100 ml	in 2% Nital	Phosphides–blue/green
2 Sodium thiosulphate	24 g	Pre-etch in 2% Nital	Phosphides–yellow/brown
Lead acetate	2.4 g	Immerse until surface	Sulphides–white
Citric acid	3 g	blue/violet	Ferrite and carbides } blue/violet
Sodium nitrite	0.2 g		
Water	100 ml		
3 Sodium thiosulphate	24 g	Pre-etch in 2% Nital	
Citric acid	3 g	(a) Immerse 20–40 s	(a) Ferrite-red/violet
Cadmium chloride	2 g	(b) Immerse 50–90 s	(b) Phosphides–orange/brown
Water	100 ml		Carbides–blue/violet Ferrite–yellow

Table 10.8 COLOUR ETCHES FOR ALUMINIUM ALLOYS

Reagent		*Procedure*	*Comments*
1 Sodium molybdate	3 g	Immersion by trial	AlCuFeMn script–blue
Ammonium bifluoride	2 g		FeSi Al–brown/blue
HCl (35%)	5 ml		Ni_3Al, FeNiAlg–brown
Water	100 ml		$CuAl_2$–pale blue
2 Chromic trioxide	20 g	Immerse 5–30 s	If alloy susceptible to inter-granular corrosion, grain boundaries coloured black
Sulphuric acid (1.84)	20 g		
Ammonium bifluoride	5 g		
Water	100 ml		
3 20% sulphuric acid (1.84)		Immerse 30 s at 70 °C	AlCuFeMn–brown
Water	80 ml		Mg_2Si–brown to black Outlines other phases
4 Sodium hydroxide	10%	Immerse 5 s at 70 °C	$CuAl_2$ } brown
Water	90 ml		Mg_2Si }

Table 10.9 ETCHING REAGENTS FOR DISLOCATIONS
(Taken largely from Lovell, Vogel and Wernick[61])

Metal or alloy	*Reagent**		*Remarks*
Aluminium (99.99%) (*see* ref. 62)	Hydrochloric acid Nitric acid Hydrofluoric acid	50% 4% 3%	--
	Hydrochloric acid Nitric acid Hydrofluoric acid	50 ml 47 ml 3 ml	Lacombe and Beaujard's reagent[69, 70]
	Hydrofluoric acid Hydrochloric acid Nitric acid Hydrogen peroxide (29% w/v)	37 ml 18 ml 9 ml 36 ml	Make: *A*, 49: 51 HF: H_2O_2 *B*, 65: 35 HCl: HNO_3 Mix in ratio A:B = 5:2, care required Keep at 0–15 °C in use (ref. 62)
Antimony	Hydrofluoric acid Nitric acid Acetic acid Bromine	3 pts 5 pts 3 pts 3 drops	Electrolytic etch on cleaved surface. 2–3 s
	Hydrofluoric acid Superoxol†	1 pt 1 pt	Electrolytic etch. 1 s
Bismuth	1% Iodine in methyl alcohol		Cleaved surface. 15 s
Brass (65% Cu–35% Zn)	0.2% Sodium thiosulphate		Electrolytic etch. 10 A dm^{-2} 18–20°C. Remove film with hydrochloric acid
Brass (Alpha)[63]	Saturated aqueous ferric chloride Hydrochloric acid	50 ml 2 drops	--
Brass (Beta)[63]	Saturated aqueous ammonium molybdate Hydrochloric acid	30 ml 6–7 drops	Immerse the electrolytically polished surface for 30 min
Columbium (Niobium)	Sulphuric acid Hydrofluoric acid Water Superoxol†	10 ml 10 ml 10 ml a few drops	Agitate specimen in solution
Copper (pure)	Saturated ferric chloride solution Hydrochloric acid Acetic acid Bromine	4 pts 4 pts 1 pt a few drops	Rinse in ammonia solution *See* Ruff[64] for further solutions and references
Germanium (also 0.2 at. % boron, 6.0 at. % silicon, 0.2 at. % tin)	Hydrofluoric acid Nitric acid Acetic acid Bromine	3 pts 5 pts 3 pts 3 drops	3–5 s. Polish etch. 600-grit carborundum ground surface
Germanium	Potassium ferricyanide Potassium hydroxide Water	8 g 12 g 100 ml	600-grit carborundum ground surface. 2–5 min. Boiling solution
Iron (99.96%)	4% metanitrobenzosulphonic acid in ethyl alcohol		Long etch. Rinse in alcohol. Result questionable
Iron	(a) 1% nitric acid in ethyl alcohol (b) 0.5% picric acid in methyl alcohol		1 min in (a) followed by rinse in methyl alcohol and 5 min in (b). Pits appear only in specimen cooled slowly from 750° to 800°C‡
	Fry's reagent Table 10.1, C(f)		10 s etch of chemically polished surface

* Acids are concentrated, unless otherwise indicated.

† Superoxol contains hydrogen peroxide (30%) 1 pt, hydrofluoric acid (40%) 1 pt, water 4 pts.

Table 10.9 ETCHING REAGENTS FOR DISLOCATIONS—*continued*

Metal or alloy	*Reagent**		*Remarks*
Iron (99.99%)	Disa Electropol solution A–Z		Electrolytic etch. Observation by electron microscopy
Iron	2% Nital containing 2% of saturated picral		15 min
	Saturated picral		4 min. Anneal to decorate dislocations‡
Iron-silicon (3.25 Si)	Acetic acid Chromium trioxide Water	133 ml 25 g 7 ml	Electrolytic etch. 3 A dm $^{-2}$. 17–19°C. Decorate with 0.004% carbon at 770°C or above in low-pressure acetylene atmosphere‡
Nickel–manganese	Orthophosphoric acid Ethyl alcohol	100 ml 100 ml	Electrolytic etch. 2 min. 200 A dm $^{-2}$ Copper cathode 40°C
Silicon	Hydrofluoric acid Nitric acid Acetic acid	1 pt 3 pts 12 pts	15 min or longer. Chemically polished surface
	Hydrofluoric acid Nitric acid 3% aqueous mercuric nitrate	4 pts 2 pts 4 pts	600-grit carborundum ground surface
	Hydrofluoric acid Nitric acid Acetic acid 3% aqueous mercuric nitrate	3 pts 5 pts 3 pts 1.5–2 pts	600-grit carborundum ground surface. Use de-ionized water. Utensils and specimen must be dry. 2 min
	Hydrofluoric acid Nitric acid Water Silver nitrate	160 ml 80 ml 160 ml 8 g	600-grit carborundum ground surface
	Hydrofluoric acid Chromium trioxide water	 50 g per 100 g	Use in ratio: 2:1 by vol. for large etch pits 1:1 for medium etch pits 2:3 for small etch pits Time 15 s[65]
Tellurium	Hydrofluoric acid Nitric acid Acetic acid	3 pts 5 pts 6 pts	1 min etch. Cleaved surface
Zinc	Chromium trioxide Hydrated sodium sulphate Water	160 g 50 g 500 ml	Immerse with mild agitation for 1 min. Chemically polish before etching. Dip in solution of 320 g chromium trioxide per litre after etching, to remove stain. Decorate with 0.1 atomic %cadmium. Anneal at 300–400°C†. Age 1 week at room temperature
Zinc with 0.002% tin[66]	Saturated aqueous ammonium tungsgtate Saturated aqueous ammonium molybdate Hydrochloric acid	35 ml 5 drops 5 drops	Etch by immersing for about 5 min. Agitate to remove adherent layer. Quench from 400°C and anneal 100–400°C‡

* Acids are concentrated, unless otherwise indicated.
‡ Note that this heat treatment must alter the dislocation structure.

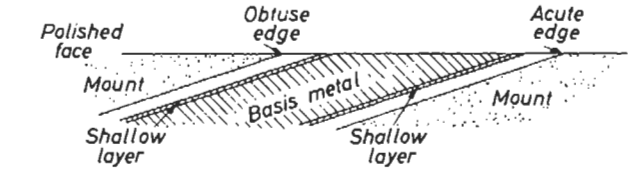
Etching to Reveal Magnetic Domains. See under IRON AND STEEL, *Microferrographic Technique*, p. **10** 39.

TAPER SECTIONING

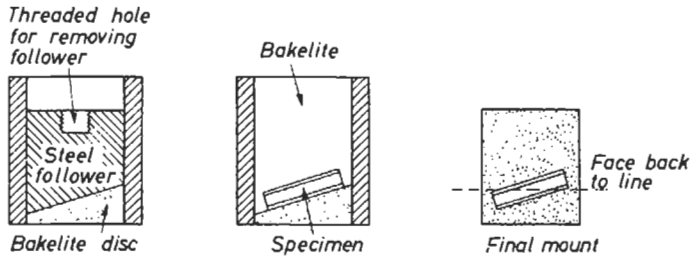
Taper-sectioning[25,26] is used to give an apparent magnification of 10 times by using a plane of section to cut the surface at a shallow angle, typically 6° (i.e. $\sin^{-1}\frac{1}{10}$) so that the vertical features of the surface are given an apparent relative magnification of about 10 times.

Taper sectioning requires plating of the surface to be examined, followed by mounting in plastic at a suitable angle. The plating may conveniently be done with nickel or copper from conventional plating baths. Assuming that the surface is ready to be examined, it must not be altered during the plating procedure; cleaning before plating must be confined to methods such as solvent washing and cathodic alkaline degreasing, which have no appreciable effect on the particular surface under examination. The mounting procedure is evident from Figure 10.3.

This method may also be used for examining thin intermediate layers, for example in electroplating or in the study of diffusion couples.



(A) Taper section



(B) Method of mounting for taper section

Figure 10.3 *Taper sectioning (from Vickers Projection Microscope Handbook)*

10.3 Metallographic methods for specific metals

10.3.1 Aluminium

PREPARATION

Aluminium and its alloys are soft and easily scratched or distorted during preparation. For cutting specimens, sharp saw-blades should be used with light pressure to avoid local overheating. Specimens may be ground on emery papers by the usual methods, but the papers should preferably have been already well used, and lubricated or coated with a paraffin oil ('white spirit' is suitable), paraffin wax or a solution of paraffin wax in paraffin oil. Silicon carbide papers (down to 600-grit) which can be well washed with water are preferred for harder alloys, the essential point being to avoid the embedding of abrasive particles in the metal. For pure soft aluminium, a high viscosity paraffin is needed to avoid this. Polishing is carried out in two stages: initial polishing with fine α-alumina, proprietary metal polish, or diamond, and final polishing with γ-alumina or fine

magnesia, using a slowly rotating wheel (not above 150 rev. min^{-1}). It is essential to use properly graded or levigated abrasives and it is preferable to use distilled water only; it is an advantage to boil new polishing cloths in water for some hours in order to soften the fibres. Many aluminium alloys contain hard particles of various intermetallic compounds, and polishing times should in general be as short as possible owing to the danger of producing excessive relief. Relief may be minimized by experience and skill in polishing; blanket felt may with advantage be substituted for velveteen or selvyt cloth as a polishing pad, while the use of parachute silk on a cork pad is also useful for avoiding relief in the initial stages of the process, but a better general alternative is to use diamond polishing, followed by a very brief final polishing with magnesia.

Many aluminium alloys contain the reactive compound Mg_2Si. If this constituent is suspected, white spirit should be substituted for water during all but the initial stages of wet polishing, to avoid loss of the reactive particles by corrosion.

The microtome technique (*see* 10.3.11, *Lead*, p. **10**–41) has been successfully applied to the softer aluminium alloys.

It should be noted that some aluminium alloys are liable to undergo precipitation reactions at the temperatures used to cure thermosetting mounting resins; this applies particularly to aluminium–magnesium alloys, in which grain boundary precipitates may be induced.

Electropolishing is often rapid and convenient (*see* Tables 10.4(a) and 10.4(b).

ETCHING

The range of aluminium alloys now in use contains many complex alloy systems. A relatively large number of etching reagents have therefore been developed, and only those whose use has become more or less standard practice are given in Table 10.11. Many etches are designed to render the distinction between the many possible microconstituents easier, and the type of etching often depends on the magnification to be used. The identification of constituents, which is best accomplished by using cast specimens where possible, depends to a large extent on distinguishing between the colours of particles, so that the illumination should be as near as possible to daylight quality. It is recommended that a set of specially prepared standard specimens, containing various known metallographic constituents, be used for comparison.

It is very easy to obtain anomalous etching effects, such as ranges of colour in certain types of particles, and carefully standardized procedure is necessary. It should be remembered that the form and colour of the microconstituents may vary according to the degree of dispersion brought about by mechanical treatments, and also that the etching characteristics of a constituent may vary according to the nature of the other constituents present in the same section.

Some etching reagents for aluminium require the use of a high temperature; in such cases the specimen should be preheated to this temperature by immersion in hot water before etching. For washing purposes, a liberal stream of running water is advisable.

Table 10.10 MICROCONSTITUENTS WHICH MAY BE ENCOUNTERED IN ALUMINIUM ALLOYS

Microconstituent	*Appearance in unetched polished sections*
Al_3Mg_2	Faint, white. Difficult to distinguish from the matrix.
Mg_2Si	Slate grey to blue. Readily tarnishes on exposure to air and may show irridescent colour effects. Often brown if poorly prepared. Forms Chinese script eutectic.
$CaSi_2$	Grey. Easily tarnished
$CuAl_2$	Whitish, with pink tinge. A little in relief; usually rounded
$NiAl_3$	Light grey, with a purplish pink tinge
Co_2Al_9	Light grey
$FeAl_3$[1]	Lavender to purplish grey; parallel-sided blades with longitudinal markings
$MnAl_6$	Flat grey. The other constituents of binary aluminium–manganese alloys ($MnAl_4$, $MnAl_3$ and 'δ') are also grey and appear progressively darker. May form hollow parallelograms
$CrAl_7$	Whitish grey; polygonal. Rarely attacked by etches
Silicon	Slate grey. Hard, and in relief. Often primary with polygonal shape—use etch to outline
α(AlMnSi)[2]	Light grey, darker and more buff than $MnAl_6$
β(AlMnSi)[2]	Darker than α(AlMnSi), with a more bluish grey tint. Usually occurs in long needles
Al_2CuMg	Like $CuAl_2$ but with bluish tinge
Al_6Mg_4Cu	Flat, faint and similar to matrix

Table 10.10 MICROCONSTITUENTS WHICH MAY BE ENCOUNTERED IN ALUMINIUM ALLOYS —*continued*

Microconstituent	*Appearance in unetched polished sections*
(AlCuMn)[3]	Grey
α(AlFeSi)[4]	Purplish grey. Often occurs in Chinese-script formation. Isomorphous with α(AlMnSi)
β(AlFeSi)[4]	Light grey. Usually has a needle-like formation
(AlCuFe)[5]	Grey α phase lighter than β phase (*see* Note 5)
(AlFeMn)[6]	Flat grey, like $MnAl_6$
(AlCuNi)	Purplish grey
(AlFeSiMg)[7]	Pearly grey
$FeNiAl_9$	Very similar to and difficult to distinguish from $NiAl_3$
(AlCuFeMn)	Light grey
$Ni_4Mn_{11}Al_{60}$	Purplish grey
$MgZn_2$	Faint white; no relief

In Table 10.10, constituents are designated by symbols denoting the compositions upon which they appear to be based, or by the elements, in parentheses, of which they are composed. The latter nomenclature is adopted where the composition is unknown, not fully established, or markedly variable. The superscript numbers in column 1 refer to the following notes:

(1) On very slow cooling under some conditions, $FeAl_3$ decomposes into Fe_2Al_7 and Fe_2Al_5. The former is micrographically indistinguishable from $FeAl_3$. The simpler formula is retained for consistency with most of the original literature.

(2) α(AlMnSi) is present in all slowly solidified aluminium–manganese–silicon alloys containing more than 0.3% of manganese and 0.2% of silicon, while β(AlMnSi), a different ternary compound, occurs above approximately 3% of manganese for alloys containing more than approximately 1.5% of silicon. α(AlMnSi) has a variable composition in the region of 30% of manganese and 10–15% of silicon. The composition of β(AlMnSi) is around 35% of manganese and 5–10% of silicon.

(3) (AlCuMn) is a ternary compound with a relatively large range of homogeneity based on the composition $Cu_2Mn_3Al_{20}$.

(4) α(AlFeSi) may contain approximately 30% of iron and 8% of silicon, while β(AlFeSi) may contain approximately 27% of iron and 15% of silicon. Both constituents may occur at low percentages of iron and silicon.

(5) The composition of this phase is uncertain. Two ternary phases exist. α(AlCuFe) resembles $FeAl_3$; β(AlCuFe) forms long needles.

(6) The phase denoted as (AlFeMn) is a solid solution of iron in $MnAl_6$.

(7) This constituent is only likely to be observed at high silicon contents.

Table 10.11 ETCHING REAGENTS FOR ALUMINIUM AND ITS ALLOYS

No.	*Reagent*		*Remarks*	
1	Hydrofluoric acid (40%)	0.5 ml	15 s immersion is recommended. Particles of all common micro-	
	Hydrochloric acid (1.19)	1.5 ml	constituents are outlined. Colour indications:	
	Nitric acid (1.40)	2.5 ml	Mg_2Si and $CaSi_2$:	blue to brown
	Water	95.5 ml	α(AlFeSi) and (AlFeMn):	darkened
			β(AlCuFe):	light brown
	(Keller's etch)†		$MgZn_2$, $NiAl_3$, (AlCuFeMn), Al_2Cu Mg and Al_6CuMg:	brown to black
			α(AlCuFe) and (AlCuMn):	blackened
			Al_3Mg_2:	heavily outlined and pitted
			The colours of other constituents are little altered. Not good for high Si alloys	
2	Hydrofluoric acid (40%)	0.5 ml	15 s swabbing is recommended. This reagent removes surface flowed	
	Water	99.5 ml	layers, and reveals small particles of constituents, which are usually fairly heavily outlined. There is little grain contrast in the matrix.	

* These are isomorphous and the colour depends on the proportion of Mn and Fe.
† Sodium fluoride can be used in place of HF in mixed acid etches.

Table 10.11 ETCHING REAGENTS FOR ALUMINIUM AND ITS ALLOYS—*continued*

No.	*Reagent*		*Remarks*	
2 (*cont.*)			Colour indications:	
			Mg_2Si and $CaSi_2$:	blue
			$FeAl_3$ and $MnAl_6$:	slightly darkened
			$NiAl_3$:	brown (irregular)
			α(AlFeSi):	dull brown
			(AlCrFe):	light brown
			Co_2Al_9:	dark brown
			(AlFeMn):	brownish tinge
			α(AlCuFe), (AlCuMg) and (AlCuMn):	blackened
			α(AlMnSi), β(AlMnSi) and (AlCuFeMn) may appear light brown to black	
			β(AlFeSi) is coloured red brown to black	
			The remaining possible constituents are little affected	
3	Sulphuric acid (1.84)	20 ml	30 s immersion at 70 °C; the specimen is quenched in cold water.	
	Water	80 ml	Colour indications:	
			Mg_2Si, Al_3Mg_2 and $FeAl_3$:	violently attacked, blackened and may be dissolved out
			$CaSi_2$:	blue
			α(AlMnSi) and β(AlMnSi):	rough and attacked
			$NiAl_3$ and (AlCuNi):	slightly darkened
			β(AlFeSi):	slightly darkened and pitted
			α(AlFeSi), (AlCuMg) and (AlCuFeMn):	outlined and blackened
			Other constituents are not markedly affected	
4	Nitric acid (1.40)	25 ml	Specimens are immersed for 40 s at 70 °C and quenched in cold water.	
	Water	75 ml	Most constituents (not $MnAl_6$) are outlined. Colour indications:	
			β(AlCuFe) is slightly darkened	
			Al_3Mg_2 and AlMnSi: attacked and darkened slightly	
			Mg_2Si, $CuAl_2$, (AlCuNi) and (AlCuMg) are coloured brown to black	
5	Sodium hydroxide	1 g	Specimens are etched by swabbing for 10 s. All usual constituents are	
	Water	99 ml	heavily outlined, except for Al_3Mg_2 (which may be lightly outlined) and (AlCrFe) which is both unattacked and uncoloured. Colour indications:	
			$FeAl_3$ and $NiAl_3$:	slightly darkened
			(AlCuMg):	light brown
			α(AlFeSi):	dull brown*
			α(AlMnSi):	rough and attacked; slightly darkened*
			$MnAl_6$ and (AlFeMn):	coloured brown to blue (uneven attack)
			$MnAl_4$:	tends to be darkened
			The colours of other constituents are only slightly altered	
6	Sodium hydroxide	10 g	Specimens immersed for 5 s at 70 °C, and quenched in cold water.	
	Water	90 ml	Colour indications:	
			β(AlFeSi):	slightly darkened
			$Mn_{11}Ni_4Al_{60}$:	light brown
			β(AlCuFe):	light brown and pitted
			$CuAl_2$:	light to dark brown
			$FeAl_3$:	dark brown
			($FeAl_3$ is more rapidly attacked in the presence of $CuAl_2$ than when alone)	
			$MnAl_6$, $NiAl_3$, (AlFeMn), $CrAl_7$ and AlCrFe:	blue to brown
			α(AlFeSi), α(AlCuFe), $CaSi_2$ and (AlCuMn):	blackened

* These are isomorphous and the colour depends on the proportion of Mn and Fe.

† Sodium fluoride can be used in place of HF in mixed acid etches.

Table 10.11 ETCHING REAGENTS FOR ALUMINIUM AND ITS ALLOYS—*continued*

No.	*Reagent*		*Remarks*
7	Sodium hydroxide Sodium carbonate (in water)	3%–5% 3%–5%	Useful for sensitive etching where reproducibility is essential. In general, the effects are similar to those of Reagent 5, but the tendency towards colour variations for a given constituent is diminished. Particularly useful for distinguishing $FeNiAl_9$ (dark blue) from $NiAl_3$ (brown). Potassium salts can be used.
8	Nitric acid Hydrofluoric acid Glycerol	20 ml 20 ml 60 ml	A reliable reagent for grain boundary etching, especially if the alternate polish and etch technique is adopted. The colours of particles are somewhat accentuated
9	Nitric acid, 1% to 10% by vol. in alcohol		Recommended for aluminium–magnesium alloys. Al_3Mg_2 is coloured brown. 5–20% chromium trioxide can be used
10	Picric acid Water	4 g 96 ml	Etching for 10 min darkens $CuAl_2$, leaving other constituents unaffected. Like reagent 4
11	Orthophosphoric acid Water	9 ml 91 ml	The reagent is used cold. Recommended for aluminium–magnesium alloys in which it darkens any grain boundaries containing thin β-precipitates. Specimen is immersed for a long period (up to 30 min). Mg_2Si is coloured black, Al_3Mg_2 a light grey, and the ternary (AlMnFe) phase a dark grey
12	Nitric acid		10 s immersion colours Al_6CuMg_4 greenish brown and distinguishes it from Al_2CuMg, which is slightly outlined but not otherwise affected
13	Nitric acid (density 1.2) Water Ammonium molybdate, $(NH_4)_6Mo_7O_{24}$, $4H_2O$	20 ml 20 ml 3 g	20 ml of reagent are mixed with 80 ml alcohol. Specimens are immersed, and well washed with alcohol after etching. Brilliant and characteristic colours are developed on particles of intermetallic compounds. The effects depend on the duration of etching, and for differentiation purposes standardisation against known specimens is advised
14	Sodium hydroxide (various strengths, with 1 ml of zinc chloride per 100 ml of solution)		Generally useful for revealing the grain structure of commercial aluminium alloy sheet[67]
15	Hydrochloric acid (37%) Hydrofluoric acid (38%) Water	15.3 ml 7.7 ml 77.0 ml	Recommended (30 s immersion at room temperature) for testing the diffusion of copper through claddings of aluminium, aluminium–manganese–silicon, or aluminium–manganese on aluminium–copper–magnesium sheet. Zinc contents up to 2% in the clad material do not influence the result[68]
16	Ammonium oxalate Ammonium hydroxide, 15% in water	1 g 100 ml	Develops grain boundaries in aluminium–magnesium–silicon alloys. Specimens are etched for 5 min at 80 °C in a solution freshly prepared for each experiment

* These are isomorphous and the colour depends on the proportion of Mn and Fe.
† Sodium fluoride can be used in place of HF in mixed acid etches.

Electrolytic etching for aluminium alloys. In addition to the reagents given for aluminium in Table 10.11, the following solutions have been found useful for a restricted range of aluminium-rich alloys:

1. The following solution has been used for grain orientation studies:

Orthophosphoric acid (density 1.65)	53 ml
Distilled water	26 ml
Diethylene glycol monoethyl ether	20 ml
Hydrofluoric acid (48%)	1 ml

The specimen should be at room temperature and electrolysis is carried out at 40 V and less than 0.1 A dm^{-2}. An etching time of 1.5–2 min is sufficient for producing grain contrast in polarized light after electropolishing.

2. The solution below is also used for the same purpose and is more reliable for some alloys:

Ethyl alcohol	49 ml
Water	49 ml
Hydrofluoric acid	2 ml (quantity not critical)

The specimen is anodized in this solution at 30 V for 2 min at room temperature. A glass dish must be used. Not suitable for high-copper alloys.

3. For aluminium alloys containing up to 7% of magnesium:

Nitric acid (density 1.42)	2 ml
40% hydrofluoric acid	0.1 ml
Water	98 ml

Electrolysis is carried out at a current density of 0.3 A dm^{-2} and a potential of 2 V. The specimen is placed 7.6 cm from a carbon cathode.

4. For cast duralumin:

Citric acid	100 g
Hydrochloric acid	3 ml
Ethyl alcohol	20 ml
Water	977 ml

Electrolysis is carried out at 0.2 A dm^{-2} and a potential of 12 V.

5. For commercial aluminium:

Hydrofluoric acid (40%)	10 ml
Glycerol	55 ml
Water	35 ml

This reagent, used for 5 min at room temperature, with a current density of 1.5 A dm^{-2} and a voltage of 7–8 V, is suitable for revealing the grain structure after electropolishing.[72]

6. For distinguishing between the phases present in aluminium-rich aluminium–copper–magnesium alloys, electrolytic etching in either ammonium molybdate solution or 0.880 ammonia has been recommended. In both cases, Al_2CuMg is hardly affected, $CuAl_2$ is blackened, Al_6Mg_4 Cu is coloured brown, while Mg_2Al_3 is thrown into relief without change of colour.[73]

GRAIN-COLOURING ETCH[74]

For many aluminium alloys containing copper, and especially for binary aluminium-copper alloys, it is found that Reagent No. 1 of Table 10.11 gives copper films on cubic faces which are subject to preferential attack and greater roughening of the surface. Subsequent etching with 1% caustic soda solution converts the copper into bronze-coloured cuprous oxide, and a brilliant and contrasting representation of the underlying surfaces is obtained. The technique is of use in orientation studies in so far as the films are dark and unbroken on (100) surfaces, but shrink on drying on other surfaces. In particular (111) faces have a bright yellow colour with a fine network on drying, which has no preferred orientation, while (110) faces develop lines (cracks in film) which are parallel to a cube edge.

ETCHING TO PRODUCE ETCH PITS[69]

The orientation of crystal grains may be determined by developed etch pits on specimens previously electropolished (*see* Table 10.4). The following reagents develop pits with facets parallel to the (100) cube planes:

	a	*b*	*c*
Fuming nitric acid	15 ml	15 ml	47 ml
Pure hydrochloric acid	45 ml	46 ml	50 ml
Hydrofluoric acid	15 ml	10 ml	3 ml
Distilled water	25 ml	29 ml	—

Mixture c is recommended where only a few large well-formed etch figures are preferred.

Etching with dry gaseous hydrochloric acid gives pits with facets parallel to (111) planes.

10.3.2 Antimony and bismuth

PREPARATION

Antimony as usually obtained is hard and brittle, and easily breaks up into fragments. Mounting in a suitably hard mounting medium is thus generally necessary, after which the usual methods are applied.

ETCHING

1. (a)	Water	22 ml	Mix equal	Sb and Sb–Bi alloys
	HNO_3 (1.40)	8 ml	quantities	
(b)	Water	30 ml	of (a) and (b)	
	Ammonium molybdate	4.5 g	immediately before use	
			~1 min	
2.	Water	100 ml	~1 min	Grain structure of Sb and Bi alloys
	Citric acid	25 g		
	Ammonium molybdate	10 g		

10.3.3 Beryllium

PREPARATION

Conventional methods may be employed, with due regard to the toxicity of beryllium. All operations which produce Be dust must be done in a glove box. Do not inhale any beryllium particles. The metal easily twins mechanically, and light hand grinding on lubricated abrasive papers is preferred. A suspension of alumina in 5% aqueous oxalic acid may be used as polishing medium on worsted serge or other short-nap cloth (cloths with longer nap may lead to pitting). The abrasive and oxalic acid are placed on the cloth before polishing begins, and the oxalic acid solution only is added as polishing proceeds. If there are soft constituents present, iron oxide (Fe_2O_3) may with advantage be substituted for alumina. Alternatively, magnesia in 30% hydrogen peroxide may be used as the polishing medium.

Other methods of preparation have been discussed,[43,76] including *electropolishing* (*see* Table 10.4).

ETCHING

1.	Hydrofluoric acid (40%)	10 ml
	Ethyl alcohol	90 ml

On immersion for 10–30 s microconstituents are in general outlined, and some colour differentiations are observed. The identifications of constituents commonly met with in commercial beryllium, both in the etched and unetched condition, are as shown in Table 10.12.

2.	Water	95 ml	1–15 s	Be alloys
	Sulphuric acid (1.84)	5 ml		
3.	Water	100 ml	2–16 min	Outlines precipitates first then grain boundaries. Better used electrolytically
	Oxalic acid	10 g		

Table 10.12 MICROCONSTITUENTS IN COMMERCIAL BERYLLIUM

Constituent	*Appearance unetched*	*Effect of etching*
Carbide	Hard angular grey particles, staining in air to many colours, finally brown	No effect on colour
Silicon-rich phase	Light blue grey	Not stained, but outlined
Nitride	Needle-like particles, darker grey than carbide	Unaffected
$TiBe_{12}$	Angular particles, slightly pink	Unaffected
$CaBe_{13}$	Light yellow, usually angular	Unaffected
$FeBe_{12}$	Almost invisible unetched	Coloured reddish brown
$MnBe_{12}$	Similar to iron, but slightly pink	Outlined
Boride	Reddish particles in grain boundaries	Coloured blue or purple
$MoBe_{22}$	Almost invisible unetched	Coloured chocolate brown
UBe_{13}	Invisible unetched	Phase revealed as a yellow or green dendritic structure
Aluminium	Bright yellow, often appearing speckled. Soft and difficult to polish	Outlined
Magnesium	Very soft, and white in appearance	Removed
$ZrBe_{13}$	Barely distinguishable dendritic phase	Outlined and coloured light blue

Beryllium can also be examined by polarized light.

10.3.4 Cadmium

PREPARATION

The preparation of cadmium for metallographic examination should be carried out in the same manner as for zinc (*see Zinc*, p. **10**–57). The metal and its alloys are soft, and very liable to mechanical twinning on deformation. *Electrolytic polishing* is satisfactory[25,43] (*see* Table 10.4).

ETCHING

	Reagent		*Conditions*	*Remarks*
1.	Ethanol	2 ml	Few seconds	Most alloys
	Nitric acid (1.40)	98 ml	to a minute	Thallium also
2.	Water	100 ml	Up to a	Eutectics of
	Hydrochloric acid (1.19)	25 ml	minute	Cd
	Ferric chloride	8 g		
3.	Water	40 ml		
	Hydrofluoric acid (40%)	10 ml	5–10 s	Most Cd alloys also thallium
	Hydrogen peroxide (30%)	10 ml		and indium

10.3.5 Chromium

PREPARATION

Normal methods may be applied successfully to chromium and its alloys, and a final electrolytic polish or attack polish is recommended (*see* Tables 10.3 and 10.4). Hard or decorative chromium

plate may be mounted in hard plastic and prepared in section by grinding in the usual way, finishing with lead laps and finally with diamond polishing.

ETCHING

Table 10.13 ETCHING REAGENTS FOR CHROMIUM

No.	*Reagent**		*Remarks*
1	Dilute hydrofluoric acid		After electropolishing with the reagent listed in Table 10.4, the specimen is agitated for a few seconds in dilute hydrofluoric acid
2	Hydrochloric acid (concentrated)		Shows striations in electrodeposits
3	Nitric acid Hydrochloric acid Glycerol	10 ml 20 ml 30 ml	Suitable for alloys. Also used electrolytically; specimen is made anode at 4 V, 45 s. Proportions 1:3:2 also used. This decomposes on standing, especially in contact with stainless steel. *Beware!*
4	Sulphuric acid (10%)		Used hot with swabbing

* Acids are concentrated, unless otherwise indicated.

10.3.6 Cobalt

PREPARATION

Normal methods, carefully applied, will suffice.

ETCHING

Cobalt may be etched with some of the reagents used for nickel and iron alloys, but some alloys are strongly resistant to attack. *See* Table 10.14.

Table 10.14 ETCHING REAGENTS FOR COBALT AND ITS ALLOYS

No.	*Reagent**		*Remarks*
1	Hydrochloric acid Nitric acid Acetic acid Water	60 ml 15 ml 15 ml 15 ml	The solution should be aged for 1 hour. Grain boundaries and the general structure of alloys are revealed. May also be used electrolytically. Of wide application, including hard metals
2	Nitric acid Hydrochloric acid Glycerol	10 ml 20 ml 30 ml	Reveals general structure. May be used electrolytically (*see* Table 10.13, Reagent 3. Same precautions
3	Potassium ferricyanide Potassium hydroxide Water	10 g 10 g 100 ml	For hard cobalt–chromium alloys containing carbon. Used at approx. 70 °C, 10–20 s. Can be replaced by electrolytic 3% KOH. Suitable for carbides
4	Chromium trioxide Sulphuric acid Water	2–10 g 10 ml 90 ml	Used electrolytically, the specimen being made the anode at 6 V

* Acids are concentrated, unless otherwise indicated.

10.3.7 Copper

PREPARATION

In general, preparation of copper and copper alloys by the usual techniques calls for no extra or special precautions. Copper itself is relatively soft, so that care is necessary to avoid excessive straining. Abrasive papers must be lubricated. Final polishing is normally carried out with slightly ammoniacal preparations, giving polish attack. Examine initially *unetched* (Table 10.15 No. 32).

ETCHING

Most homogeneous copper alloys have much the same etching characteristics as copper, and the same etching reagents as are used for copper may be tried. Alloys containing more than one phase usually etch easily, but careful attention must be paid to the time of etching. When using chromic acid solutions, sulphate ions should preferably be absent, as their presence leads to uneven action. In general, etches comprise (a) ammonia plus oxidizing agent, (b) acidified chromic acid or dichromates; the latter is good as an electrolytic etch.

Table 10.15 ETCHING REAGENTS FOR COPPER AND ITS ALLOYS

Principal use	*No.*	*Reagent*	*Remarks*
Copper, copper alloys in general. Brass, bronze and nickel–silver	*1*	Ammonium hydroxide 50 ml Water 50 ml Hydrogen peroxide (30 vol.) 20 ml	Used for copper, and many copper-rich alloys. Gives a grain boundary etch, and also tends to darken the α solid solution, leaving the β solid solution lighter. The hydrogen peroxide content may be varied. Less is required the lower the copper content (*see* Reagent 2)
	2	Ammonium hydroxide 50 ml Water 50 ml Hydrogen peroxide (30 vol.) 10 ml	Used for bronze, 70:30 and 60:40 brasses; this etch may with advantage be followed by a ferric chloride etch (Reagent 6) to darken the β areas in duplex alloys
	3	Ammonium hydroxide 10 ml Water 10 ml Ammonium persulphate, 2½% solution 10 ml	Recommended for polish attack on copper and copper alloys
	4	Ammonium persulphate 10 g Water 100 ml	Used cold or boiling for copper, brass, bronze, nickel-silver and aluminium-bronze. Tends to produce relief effects. Good for aluminium bronzes followed by Reagent 23 to darken β martensite (retained β is pink) and then Reagent 24 to etch $\gamma_2(\delta)$ brown
	5	Dilute ammonium hydroxide solution (10–50%)	May be used for polish or swab attack on brass and bronze. The oxidising action of atmospheric oxygen is necessary for the process
	6	Ferric chloride, various strengths and compositions. To 100 parts of water are added: Hydrochloric acid (1.19) — Ferric chloride (g) 20 — 1 10 — 5 50 — 5 25 — 8 6 — 19 25 — 25 1 — 10† 10 — 3‡	Used as a general reagent for copper, brass, bronze, nickel–silver, aluminium–bronze and other copper-rich alloys. It darkens the β constituent in brasses and gives grain contrast following ammoniacal or chromic acid etches. The most suitable composition should be found by trial and error in specific cases. This reagent generally emphasizes scratches in imperfectly prepared specimens, and tends to roughen the surface. For sensitive work it is frequently a great advantage to replace the water in the reagent by a 50:50 water–alcohol mixture or by pure alcohol

† Usually used with 1 part of chromic acid CrO_3.
‡ Used with 1 part of cupric chloride and 0.05 parts of stannous chloride.

Table 10.15 ETCHING REAGENTS FOR COPPER AND ITS ALLOYS—*continued*

Principal use	*No.*	*Reagent*	*Remarks*
Copper, copper alloys in general. Brass, bronze and nickel–silver (continued)	*7*	Ethyl alcohol (commercial) 96 ml Ferric chloride (anhydrous) 59 g Hydrochloric acid 2 ml	Dilute 5:1 with alcohol. Wash with alcohol or acetone. More delicate and controllable than aqueous solutions
	8	Chromic acid CrO_3 saturated in water	Used for copper, brass, bronze and nickel-silver. The etching time is 1 to 1½ min. Grain boundaries are attacked and β constituents are coloured pale yellow, while the primary solid solution is coloured dark yellow
	9	Chromic acid, 100–150 g l^{-1} of water, 1–2 drops of hydrochloric acid are added immediately before use to a 50 ml portion	Used for copper, brass, bronze, nickel-silver, and recommended for revealing the silicides of Ni, Co, Cr and Fe in certain alloys. Alternate polishing and etching is recommended, when a grain contrast is obtained. The primary solid solution is not attacked. The β copper-zinc phase is coloured light yellow while the δ copper-tin phase is coloured brown to black. The reagent may be followed by a ferric chloride etch
	10	Chromic acid 25 g Nitric acid (1.40) 40 ml Water 35 ml	This reagent is useful for distinguishing the general constituents of many copper alloys. The γ and δ phases are particularly well shown up as shining blue crystals
	11	Sulphuric acid (1.84) 5 ml Potassium dichromate saturated in water 100 ml	Etching time ½ to 1 min. Suitable for copper, but attacks oxide inclusions strongly
	12	Nitric acid, various strengths	Used for any purpose requiring deep etching and the removal of a thick layer of surface material. The times of etching are short and difficult to control
	13	Sulphuric acid (1.84) 5 ml Hydrogen peroxide (10 vol.) 100 ml	Etching time 1 to 1½ min. Used for pure copper, but attacks oxide
	14	Silver nitrate, 100 g l^{-1} of water, following exposure to hydrogen sulphide	This technique has been used for 70:30 and 60:40 brasses, and produces satisfactory contrast
	15	Silver nitrate, 20 g l^{-1} of water	Immerse for 30 s, and wash off silver stain under water. Useful in certain cases for pure copper
	16	Ammonium hydroxide 10 ml Ammonium oxalate saturated in water 30 ml	Used for high-zinc brasses
	17	Ammonium hydroxide 10 ml Potassium arsenate saturated in water 30 ml	Used for high-zinc brasses
	18	Copper ammonium chloride. 100 g l^{-1} of water, plus ammonium hydroxide to slight alkalinity	Copper, brass and nickel-silver. Specially recommended for darkening large β areas in duplex brasses
	19	Ammonia 20 ml Potassium permanganate (0.4%) in water 30 ml	Used for pure copper. Etching time 2 to 3 min. Liable to produce staining
	20	Bromine water, saturated	Etching time 30 to 60 s. May be used satisfactorily with pure copper if the coating which forms is removed by washing in strong ammonia

Table 10.15 ETCHING REAGENTS FOR COPPER AND ITS ALLOYS—*continued*

Principal use	*No.*	*Reagent*		*Remarks*
Aluminium–bronze	*4*	See above		As for Reagent 4
	6	See above		As for Reagent 6. Darkens β
	10	See above		As for Reagent 10. Also generally useful for aluminium-bronzes
	21	Chromic acid Nitric acid (1.40) Water	20 g 50 ml 30 ml	Recommended for aluminium-bronze after pretreatment with 10% hydrofluoric acid solution in order to remove surface oxide films
	22	Chromic acid Nitric acid (1.40) Water	20 g 5 ml 75 ml	As for Reagent 21
	23	Nitric acid (1.40) Hydrogen peroxide (100 vol.)	0.5 ml 99 ml	Darkens martensite
	24	Sod. hydroxide Water	10 g 100 ml	γ_2 (δ) etched brown
Aluminium–bronze	*25*	Ferric nitrate Ammonium nitrate Nitric acid Water	20 g 20 g 2 ml 500 ml	Good for complex aluminium bronzes
	26	Ammonium hydroxide Water Hydrogen peroxide 3% solution	25 ml 25 ml 20 ml	Age 1 week in loosely stoppered bottle before use. To distinguish eutectoid ($\alpha+\gamma_2$) from acicular $\beta.\gamma_2$ attacked
Copper alloys with beryllium, silicon, manganese and chromium	*8*	—		As for Reagent 8. Is also useful for manganese bronze
	27	Potassium dichromate Water Sodium chloride (saturated) Sulphuric acid (s.g. 1.84)	2 g 100 ml 4 ml 8 ml	Used for copper, and copper alloys with beryllium, manganese and silicon. Also suitable for nickel–silver, bronzes and chromium–copper alloys. This reagent should be followed by a ferric chloride etch to give added contrast
High-nickel alloys	*28*	Nitric acid (s.g. 1.42) Glacial acetic acid Water	50 ml 25 ml 25 ml	Recommended for high-nickel alloys which might prove resistant to attack by the more usual reagents, and for bright copper electrodeposits. 1:1 nitric acid : acetic acid is also used
Copper–nickel–aluminium	*29*	Acetic acid, 75% Nitric acid Acetone	30 ml 20 ml 30 ml	Recommended for copper-rich copper–nickel–aluminium alloys. NiAl shows as dove-grey rectangular needles; Ni_3Al is globular and darker grey. The γ_2 phase of the aluminium–copper system is a pale grey; *see also* Reagent 24
Copper–silicon alloys	*30*	Hydrogen peroxide (30 vol.) Water Potassium hydroxide (20%) Ammonium hydroxide (s.g. 0.90)	20 ml 25 ml 5 ml 50 ml	Used specifically to distinguish the κ phase in copper–silicon alloys, and in ternary and more complex alloys based on this system.
Leaded copper and bearing metals of this material	*31*	Nitric acid Glacial acetic acid Glycerol	20 ml 20 ml 80 ml	General reagent for leaded copper, bronzes, etc. *See* below for further notes on leaded coppers. Darkens lead
	32	Trichloroacetic acid Water Ammonium hydroxide to make 100 ml	20 g 20 ml	As for Reagent 31. Etches and outlines lead constituent, bringing it into prominence. Monochloroacetic acid may be substituted

Table 10.15 ETCHING REAGENTS FOR COPPER AND ITS ALLOYS—*continued*

Principal use	*No.*	*Reagent*	*Remarks*
Macro-etching	*33*	Heat tinting	This technique occasionally gives useful results. Phosphor bronzes react the most favourably
	34	No etching	Several constituents which may be present may be observed in unetched sections. Thus the selenide and telluride appear blue grey, while the oxide appears blue. Metallic bismuth appears a very pale blue grey. Cuprous oxide, unless the particles are very small, appears ruby-red in polarised light or with dark-field illumination; selenide and telluride remain dark. Zinc oxide (in brass) appears transparent and anisotropic in polarised light, blue-grey with ordinary illumination

LEADED COPPER ALLOYS

Difficulties can arise in the preparation and examination of leaded alloys, owing to the different hardnesses of the constituents, and also because specimens are particularly subject to smearing of the lead over the copper matrix. The standard methods of preparation properly applied, i.e. hand grinding on lubricated papers, followed preferably by diamond polishing, are quite satisfactory. Lead particles may be observed on properly polished unetched surfaces; it is essential that any flowed polished layer should be removed before observation by etching (Reagent 9 is suitable) and the surface again lightly polished before examination. For the best results it may be advisable to repeat the alternate etching and polishing two or three times. If it is necessary to etch, Reagents 31 and 32 of Table 10.15 may be used to etch the lead, or ferric chloride or chromic acid reagents to attack the copper-rich matrix.

The dithizone process described under *Iron and steel* (p. **10–38, 10–39**) is also applicable to brasses. (*See also Electrolytic etching*, below.)

Table 10.16 ELECTROLYTIC ETCHING OF COPPER ALLOYS

Principal use	*No.*	*Reagent*		*Remarks*
General	*1*	Ferrous sulphate Sodium hydroxide Sulphuric acid (1.84) Water	30 g 4 g 100 ml 1900 ml	May be used to develop contrast after the use of ammoniacal hydrogen peroxide reagents. β in brasses is darkened. A current density of 0.1 A dm^{-2} at 8–10 V is suitable
Cupro–nickel and nickel–silvers	*2*	Citric acid	100 g/l	Also useful for brasses
	3	Ammonium molybdate in excess of ammonia		Also useful for brasses
	4	Glacial acetic acid Nitric acid (1.40) Water	5 ml 10 ml 85 ml	This reagent tends to minimize the effect on the microstructure of the coring which usually occurs with these alloys
Brasses	*5*	Ammonium acetate 100 g l^{-1} of water		Current density 0.3 A dm^{-2}
	6	Ammonium sulphate 10 g l^{-1} of water		Current density 0.3 A dm^{-2}
	7	0.10 M ammonium acetate 0.50 M sodium thiosulphate 14 M ammonium hydroxide Distilled water	10 ml 30 ml 30 ml 30 ml	Carried out at 31 A dm^{-2}. The etching time is approximately inversely proportional to the copper content of the material

Table 10.16 ELECTROLYTIC ETCHING OF COPPER ALLOYS —*continued*

Principal use	*No.*	*Reagent*		*Remarks*
	8	Chromic acid CrO_3 170 g l^{-1} of water		Useful for distinguishing the γ and ε phases of the copper–zinc system. At current densities above 23 A dm^{-2} the γ phase is attacked, but not the ε phase. At low current densities the order of the attack is reversed. The zinc-rich solid solution is attacked under both conditions.
Aluminium–bronze and copper–beryllium alloys	*9*	Chromic acid Water	10 g 900 ml	This reagent is satisfactory for all stages of heat treatment, and is useful for following the stages of precipitation in the age-hardening of copper–beryllium alloys. Distilled water must be used as tap water leads to staining. A potential of 6 V, with an aluminium cathode, is satisfactory
Leaded copper and brass	*10*	Dilute sulphuric acid (up to 10% by vol)		Electrolytic etching at 6 V, with a carbon cathode, has been recommended for lead-bearing copper and brass, in order to avoid misinterpretation of the structure due to surface flow

ELECTROLYTIC ETCHING OF COPPER ALLOYS

Copper alloys in general are particularly suitable for electrolytic etching, and this technique frequently gives good results with alloys (e.g. high-nickel alloys) which are otherwise difficult to etch. Solutions which have been found effective are given in Table 10.16; potential differences and current densities must be adjusted to suit specific materials. Reagents listed for electrolytic polishing of copper (Table 10.4) may also be tried.

A very sensitive etching of homogeneous copper alloys may be obtained by electrolytically polishing in phosphoric acid solution (1000 g l^{-1}), and short-circuiting the electrodes when polishing is complete. The polarisation current set up gives anodic action at the crystal boundaries only.

10.3.8 Gold

PREPARATION

Gold and its alloys are soft, and care in the application of the usual techniques is necessary.

ETCHING

The five solutions given in Table 10.17 are of general suitability.

Table 10.17 ETCHING REAGENTS FOR GOLD AND ITS ALLOYS

No.	*Reagent*		*Remarks*
1	Potassium cyanide, 10% in water Ammonium persulphate, 10% in water	10 ml 10 ml	Used for gold and its alloys. A fresh solution, warmed if necessary, must be used for each experiment. The etching time varies from ½ to 3 min. The attack may be speeded up by the addition of 2% of potassium iodide, but this is liable to give staining effects
2	Tincture of iodine, 50% solution in aqueous potassium iodide		Used for gold alloys. With silver–gold alloys a silver iodide film may form. This may be removed by immersion in potassium cyanide solution

Table 10.17 ETCHING REAGENTS FOR GOLD AND ITS ALLOYS—*continued*

No.	*Reagent*	*Remarks*
3	Aqua regia (20 ml conc. nitric acid + 80 ml conc. hydrochloric acid)	The hot solution is used. If much silver is present a silver chloride film may form; this may be removed by ammonium hydroxide or potassium cyanide solutions. Use fresh only; liable to decompose with evolution of chlorine and NO_2
4	Potassium sulphide solution	Solution used hot; particularly useful for gold–nickel alloys
5	Chromic acid (chromium trioxide) 3 g Hydrochloric acid (1.19)	Gold-rich alloys (up to 1 min)

ELECTROLYTIC ETCHING OF GOLD

The microstructure of gold may be developed by anodic treatment in concentrated hydrochloric acid to which a little ferric chloride has been added.

Dilute solutions of hydrochloric acid, potassium cyanide or potassium cyanide plus potassium iodide may also be used.

10.3.9 Indium

PREPARATION

The pure metal and many of its alloys are very soft, and should in general be prepared by the methods recommended for lead or cadmium. It is frequently sufficient to cut suitable specimens with a sharp razor blade. After very light grinding, which may be carried out with carborundum in soap solution on broadcloth, specimens may be polished with alumina suspended in soap solution on silk nap cloth.[77,78]

ETCHING

Etching reagents containing hydrofluoric acid, nitric acid, or mixtures of the two acids, are in general satisfactory, and the following are recommended for indium-rich alloys:[77,78]

Note that an acid solution plus an oxidizing agent is the basis of etches for indium.

1. Potassium dichromate	1.3 g	
Sulphuric acid conc. (1.84)	4.5 ml	
Saturated sodium chloride solution	2.7 ml	
Hydrofluoric acid (40%)	17.7 ml	
Nitric acid conc. (1.40)	8.8 ml	
Water	66.3 ml	Use up to 1 min
2. Hydrochloric acid (1.19)	20 ml	
Picric acid	4 g	
Ethyl alcohol	400 ml	

For alloys containing bismuth it is necessary to increase the proportions of alcohol and hydrochloric acid.

10.3.10 Iron and steel

PREPARATION

Iron and low carbon steels are particularly susceptible to surface deformation during preparation, so that grinding must be carefully carried through, without undue straining or pressure. The development of heat in the surface must also be avoided; the heating of a thin skin, as a result of defective grinding, followed by rapid loss of heat by condition inwards, may easily produce

martensitic patches on the surface of some unhardened alloy steels, so that in these cases special care should be taken. In the same way, retained austenite can be produced in tool steels if uncorrectly ground. Specimens may be adequately cooled in cold water. In general, it is an advantage to remove the cold-worked surface layer progressively by alternate polishing and etching. Reagents 1 and 2 in Table 10.18 are suitable. Polishing with diamond powder, using a coarse grade (8 μm) for preliminary polishing and a fine grade ($\frac{1}{2}$–1 μm) for a second stage, gives very good results with good retention of inclusions. This may be followed by a brief alumina polish.

Galvanized steel is best prepared by diamond polishing, using white spirit as a lubricant. This avoids attack of the zinc due to potential differences set up between the zinc and the basis metal with aqueous polishing media. The preparation is very flat, thus facilitating examination of diffusion layers.

A similar technique may be employed for tin-plate.

MICROGRAPHIC CONSTITUENTS OBSERVED

The metallography of iron and steel is complex, and the various constituents likely to be observed may be very briefly summarized as follows:

1. *Ingot iron and wrought iron.* These consist mainly of *ferrite* (α-iron; body centred cubic crystal structure), the etching characteristics of which may be affected by phosphorus, manganese or silicon in solid solution, or by the presence of slag inclusions. Carbon is usually present to the extent of 0.15–0.25%, and is revealed as *cementite* (iron carbide Fe_3C). Sulphur may be present as *iron sulphide.*

2. *Normalized and annealed carbon steels.** The microconstituents present vary according to the carbon content. Below 0.9% of carbon, specimens consist of *ferrite* and a closely intermingled eutectoid mixture of *ferrite* and *cementite* which is known as *pearlite* and occurs as a characteristically finely laminated structure. At 0.9% of carbon, specimens are entirely *pearlite.* Above 0.9% of carbon the constituents are a network of massive *cementite* surrounding *pearlite* areas. Normalized and annealed steels differ in the character and extent of the pearlitic areas, which are usually coarser in the latter case. Very rapid cooling gives very fine, almost unresolvable pearlite. Heating at 700 °C leads to the formation of *globular cementite*, resulting from the coalescence of eutectic cementite. Prolonged heating of high carbon steels at 800 °C decomposes cementite into *ferrite* and free *graphite*, which must be considered as a possible constituent.

3. *Hardened and tempered carbon steels.* At a high temperature (above that at which the transformation of α- into γ-iron takes place) carbon steels consist of *austenite*, a solid solution of carbon in γ-iron. This is rarely retained by quenching (some austenite is retained in highly alloyed steels such as the tool steels). In most steels a variety of decomposition products may arise depending on the severity of quenching locally. The structures obtained are:

(a) Martensite, which requires most rapid quenching. This is recognized as an intersecting system of parallel or lenticular needles (acicular structure). In highly alloyed steels some residual austenite may be retained in between the needles. Electron microscopy is needed for a detailed study of martensite. In low and medium carbon steels and maraging steels, *lath martensite* is formed and has a parallel-banded structure containing high densities of dislocation. This is characteristic of martensite formed at relatively high temperatures (i.e. 200 °C and above).
In high carbon steels and iron–nickel steels, *twinned acicular martensite* is formed. This is often lenticular with internal twinning. It forms below about 150 °C. Mixtures of lath and acicular martensite are found in medium carbon steels.

(b) Bainite is formed at lower rates of quenching. It is a non-lamellar aggregate of ferrite and cementite.
Upper bainite comprises bundles of parallel laths of ferrite between which carbide precipitates. While it can form by continuous cooling, it is more usually a consequence of isothermal decomposition of austensite at 400–500 °C. It etches up more darkly the lower the temperature at which it forms, but the structure is only seen in clear detail by electron microscopy. The transformation does not usually go to completion and residual austenite transforms to martensite at lower temperatures.

* By 'normalizing' is meant the reheating of a steel to a temperature at which it consists of a solid solution of carbon in γ-iron, followed by free cooling in air. By 'annealing' is meant the reheating of a steel to a similar temperature for an appreciable time, followed by slow cooling, usually in a furnace.

Lower bainite is more usually found in steels quenched too slowly to form fully martensitic structures. Like upper bainite, it is diffusion controlled but forms at lower temperatures, usually below 350°C. It is difficult to distinguish from a tempered martensite by optical examination and needs electron microscopy for full identification. It is acicular or plate-like with subsidiary plates or needles nucleated from existing plates (unlike upper bainite, which is nucleated from austenitic boundaries). Lower bainite comprises ferrite plates or needles with carbides precipitated internally on one orientation. (In tempered martensite, two or more orientations of carbides are found.) Lower bainite is also free from twins.

(c) Pearlite. This is a lamellar eutectoid of iron and cementite, the spacing of which is dependent on the temperature at which it forms. It nucleates as nodules which grow from prior austenitic grain boundaries or in low carbon steels from ferrite/austenite interfaces.

(d) In alloy steels, manganese sulphides replace iron sulphides.

(e) In cast irons, similar structures are found but the higher carbon content results in either primary cementite or flakes of graphite depending on alloy content and/or cooling rate. Graphite can also be present as a eutectic or as nodules. By careful preparation, the structure of graphite can be revealed by polarized light. Phosphorus introduces a characteristic eutectic of ferrite and Fe_3P or a ternary eutectic with Fe_3C.

ETCHING OF IRON, STEEL AND CAST IRONS

Etching reagents are used for two purposes:

1. To reveal the general structure of the steel for which a few reagents can be used for most steels.
2. To differentiate various carbides or to differentiate carbides from nitrides and other constituents. For these an enormous variety of quite complex reagents has been developed. It is often difficult to reproduce the effects claimed by those skilled in the use of these reagents. In more complex steels, these reagents are used hot. In general, most reagents are based on an alkaline solution containing a mild oxidizing reagent and a chemical likely to cause selective staining of the minor phases. It is often simpler and equally effective to use a 1–10% caustic potash solution electrolytically with the specimen as anode. Many solutions are recommended to be used hot for the more highly alloyed and etch-resistant steels, but they can equally well be used cold as electrolytic etches. In Table 10.18 a few tried and reliable etches are given which should be used before considering the more complex etches in the literature.

LEAD IN STEELS

Lead particles in free-cutting steels can be revealed by three reagents:

1. 10% ammonium acetate in water	Brown stains on lead particles after 30 s immersion.
2. 30 g potass. dichromate 225 ml water (hot to aid solution) 30 ml acetic acid added to cold solution	10–20 s etch reveals lead as yellow to gold particles under cross-polars with polarized light. (Steel not etched)
3. 1 g potass. cyanide 100 ml water, mixed with 0.25 g diphenyl diacarbazone in 10 ml chloroform	Etch first in picrate. Rinse and dry. Then swab with this solution. Lead coloured red, especially under polarized light

The general distribution of lead can be displayed by the following:

1. Etched ground surface in nitric acid, wash and dry.
2. Cover for 5 min with absorbent paper soaked in mixture of 50% glacial acetic acid and 50% of 10% chromium trioxide in water.
3. Strip paper and wash with 10% acetic acid leaving yellow lead chromatic colouration. Wash with water.

4. Develop paper in either the third etchant above or in 1% potassium cyanide in 100 ml water plus 10 ml of 0.1% solution of dithizone in chloroform. After washing and drying, the distribution of lead is indicated by red spots. (This is generally appliable to distribution of lead in metals, e.g. in brasses.)

INCLUSIONS IN STEEL

Many of these can be recognized by shape and colour without etching and can be identified positively by EDAX analysis on scanning electron microscopes. The following notes are a useful guide to a quick optical assessment.

Iron phosphide	Brilliant white, especially in cast irons. Distinguished from cementite (Fe_3C) by alkaline potass. ferricyanide which darkens phosphide before cementite or by alkaline sod, picrate which darkens cementite
Iron nitride	Bluish grey. Not attacked by alkaline potass. ferricyanide. Coloured yellow in 4% picric acid in ethanol
Iron sulphide	Brownish yellow
Manganese sulphide	Dove grey. Ferrous sulphide is attacked by 1% oxalic acid in water; manganese sulphide is attacked by 10% chromic acid in water. Both deformed by hot rolling
Chromium oxide	Dark bluish grey; brilliant green under polarized light (crossed polars)
Silicates	Iron silicate dark grey; manganese silicate somewhat lighter, greenish tint. Often glassy as spheres which show 'optical cross' under polarized light
Titanium nitride	Sections of golden yellow cubes. If large amounts, dendritic growth from corners of cube but this is rare
Zirconium nitride	As TiN but more lemon yellow
Alumina	Angular particles in groups not elongated by rolling
Silica	Dark angular particles, often not elongated by rolling

FERROMAGNETIC ANALYSIS

To distinguish between magnetic and non-magnetic phases, e.g. ferrite from austenite in iron–chromium–nickel alloys, a thin film of a colloidal suspension of magnetic particles is applied to the surface of a specimen subject to a magnetic field. The particles concentrate on the magnetic constituent, usually in a characteristic banded or mosaic pattern. The following suspension has been recommended.[80]

A coarse flaky precipitate of magnetite is prepared by dissolving 2 g of $FeCl_2 \cdot 4H_2O$ and 5.4 g of $FeCl_3 \cdot 6H_2O$ in 300 ml of hot water, and adding, with constant stirring, 5 g of caustic soda in 50 ml water. The precipitate is filtered, washed with water and with 0.1 N hydrochloric acid. On transferring the precipitate to 1 l of 0.5% soap solution and boiling, a colloidal suspension is obtained, which should be filtered from the unsuspended residue. The suspension may now be applied to the surface of the specimen, which is placed in the field of an electric magnet. The magnetic properties of the particles gradually deteriorate owing to oxidation. The addition of small amounts of photographic reducing agents has been found an advantage in this connection.[80]

Table 10.18 ETCHING OF IRON STEEL AND CAST IRONS
(*See also* refs 1 and 2 for extended list of etchants)

No	*Etchant*		*Conditions*	*Remarks*
1	Nitric acid (1.40) Ethanol (Nital)	1.5–5 ml to 100 ml	5–30 s depending on steel	Ferrite g.b.'s in low carbon steels. Darkens pearlite and gives contrast with ferrite or cementite network. Etches martensite and its decomposition products in many steels. Better than Picral for low alloy steels and for ferritic grain boundaries

Table 10.18 ETCHING OF IRON STEEL AND CAST IRONS—*continued*
(*See also* refs. 1 and 2 for extended list of etchants)

No.	*Etchant*		*Conditions*	*Remarks*
2	Picric acid Ethanol (Picral)	4 g 100 ml	5–30 s depending on steel	Similar to Reagent 1 but gives more uniform etch of pearlite. Better for detail of pearlite and martensite. Reveals undissolved carbides in martensite and gives better distinction of carbides in spheroidized steels. Differentiates pearlite and bainite
3	50/50 mixture of Reagents 1 and 2		5–30 s depending on steel	Used for low alloy steels. Gives lower contrast but more even etching than Reagent 1
4	HCl (1.19) Picric acid Ethanol (5 ml HCl and 1 g picric acid usually referred to as Vilella's reagent)	1–5 ml 1–4 g to 100 ml	5–10 s	Attacks prior austenite boundaries; increased contrast between grains. (Attack of boundaries in martensite alloys increased if tempered for 30 min at 310 °C)
5	Chromium trioxide Water Sodium hydroxide (add carefully)	16 g 145 ml 80 g	10–30 min in boiling solution	Reveals intergranular oxidation of medium carbon alloy (nickel) steels
6	Sod. metabisulphite Water	8–20 g to 100 ml	5–60 s	Increases contrast in martensitic steels; distinguishes pearlite, bainite and martensite in high carbon alloy steels
7	Picric acid Sod. hydroxide Water	2 g 25 g to 100 ml	Either 10 s to 2 m. boiling soln. or electrolytically cold at 0.5–2 A ft^{-2} for 2 min (stainless steel cathode)	Blackens cementite (in alloy with 10% Cr). No effect on M_7C_3, $M_{23}C_6$, M_6C or MC
8	Potass ferricyanide Potass. or sod. hydroxide (Murakami's reagent)	10 g 10 g to 100 ml	2–20 min at 20–50 °C (or electrolytically as Reagent 7	Cementite in alloys > 10%Cr stained black. M_7C_3, $M_{23}C_6$ and iron phosphide stained. In cast irons, immerse 10 s at 80 °C to darken iron phosphide, then 30 s at 80 °C to darken cementite unaffected by 10 s immersion. In stainless steels, carbides darken, sigma phase blue, ferrite yellow
9	Nitric acid (1.40) Hydrochloric acid (1.19) Glycerol (also known as Vilella's reagent but do not confuse with Reagent 4; also called glyceregia)	10 ml 20 ml 30 ml	Immerse up to 30 s or use electrolytically with stainless steel cathode *Do not keep, discard when yellow, gives off chlorine and NO_x. Do not leave in contact with stainless steel*	Etches high chromium cast irons, stainless steel and high chromium steels
10	Sod. hydroxide Water	45 g to 100 ml	5–60 s Electrolytic with 1–3 V d.c. stainless steel or Pt cathode	In stainless steels, sigma and chi phases yellow to reddish brown (chi etches before sigma), ferrite blue grey, carbides outlined after longer etch
11	Potass. permanganate Sod. hydroxide Water	10 g 4 g to 100 ml	1–10 min in boiling soln. Electrolytic for 5–30 s as Reagent 10	In tool steels, blackens M_7C_3 and $M_{23}C_6$, outlines MC (VC)
12	Ferric chloride Hydrochloric acid (1.19) Water (Kalling's reagent)	2 g 5 ml 30 ml	Immerse 1–5 min	In tool steels attacks ferrite and martensite, outlines carbides, leaves austenite unattacked

Table 10.19 ELECTROLYTE ETCHING OF STEELS
Some etches in Table 10.18 can be used electrolytically.
The following are used exclusively electrolytically

No.	*Etchant*		*Conditions*	*Remarks*
1	Lead acetate Water	10 g to 100 ml	2 V d.c. Stainless steel cathode 5–20 s	In Fe–Cr–Ni cast alloys Sigma phase blue red Ferrite Dark blue Austenite Pale blue Carbides Yellow
2	Ammonium hydroxide (0.88)		2–6V d.c. Pt cathode 30–60s	Stainless and high alloy steels. Etches carbides; sigma phase unattacked
3	Chromium trioxide Water	10 g to 100 ml	3–6 V d.c. Pt cathode 5–60 s	Stainless steels. Carbides outlined and attacked. Austenite, ferrite, phosphide attacked in that order
4	Oxalic acid Water	10 g to 100 ml	6 V d.c. Stainless steel cathode 5–60 s	Outlines carbides first then grains in stainless steels
5	Potass, or sod. hydroxide Water	1 g to 100 ml	1–6 V d.c. Stainless steel cathode 5–30 s	By control of voltage, can be made to etch various phases sequentially. High voltages outline carbides and grains. Low voltages selectively stain phases in sequence. Establish behaviour on a given composition (which applies to most electrolytic etches)

10.3.11 Lead

PREPARATION

The preparation of lead and its alloys for micrographical examination is difficult, owing to the softness of the metal. Samples should be cut very gently with a sharp, oiled hacksaw. Grinding may be carried out by hand on well paraffined emery paper, and a very gentle pressure used (otherwise the surface will be badly smeared). It is advisable to finish the grinding on a well-worn paper which has been preserved from contamination by atmospheric dust. The use of a sharp, chisel-edged tool on a lathe, or of a microtome is, however, greatly to be preferred to grinding. A number of progressively finer cuts is taken, the finest possible cut being used at the last stage. The flowed layers remaining after this operation are removed by alternate etching (Reagent 15 in Table 10.20 is suitable) and polishing (e.g. with 'Bluebell' metal polish on Selvyt cloth). This is continued until all evidence of distorted or recrystallized metal is removed. A final polish is then given using a slurry of fine magnesia and water on a Selvyt cloth. Alternatively, the pad may be dressed with soap and polishing done with fine γ-alumina. Chemical polishing in 75 ml acetic acid and 25 ml hydrogen peroxide is also recommended (*see* Table 10.1).

ETCHING

Satisfactory light etches are obtained only if the degree of polish is high and the flowed layer thin. In many cases it is possible to improve results by alternate light etching and polishing as stated above. In all etching experiments fresh solutions should be used, and the specimen well washed and dried with hot air after rinsing with acetone. Rapid tarnishing (oxidation) of polished and etched samples may be avoided by attention to the drying procedure (p. **10**–18). Surfaces properly finished may be preserved unchanged for some days. Certain alloys, particularly antimonial, may be preserved by washing in strong sodium hydroxide solution, rinsing in dilute soap solution, and drying. A transparent preservative film is formed on the surface.

Suitable reagents are given in Table 10.20.

ELECTROLYTIC ETCHING OF LEAD ALLOYS

Lead and its alloys may be etched electrolytically, in many cases with a saving of time and with better control, in a solution containing 40 ml of perchloric acid and 60 ml of water Good results are obtained in 10 s at a potential of 2 V.

Table 10.20 ETCHING REAGENTS FOR LEAD AND ITS ALLOYS

No.	*Etchant**	*Remarks*
1	Nitric acid	Recommended for pure lead. Specimen is alternately etched and washed until the desired result is obtained. Macro etch mainly
2	Acetic acid 5% in alcohol	Slow-acting grain contrast etch for lead
3	Perchloric acid 600 g l^{-1} of water	Of general application
4	Acetic acid 30 ml Hydrogen peroxide (30 vol.) 10 ml	This is recommended as a general-purpose reagent for lead, and its alloys with tin, antimony, calcium, sulphur, selenium and tellurium, as well as many other metals. The proportions may have to be adjusted slightly to suit individual cases. The reagent may be made somewhat less vigorous by dissolving a little lead in it before use. The usual etching time is 3–5 s. The action is exothermic and may give rise to recrystallization and grain growth if continued for too long a time. The reagent should not be kept for more than 1 h. It is recommended that the surface of the specimen be cleaned after etching with nitric acid. (*See also* Table 10.5)
5	Acetic acid 30 ml Nitric acid 40 ml Water 160 ml	Used at 40–42 °C for lead, and lead-tin alloys rich in lead
6	Acetic acid 10 ml Nitric acid 10 ml Glycerol 40 ml	This reagent is recommended when the alternate etching and polishing technique is employed. Used for lead, lead–calcium alloys and lead–antimony and lead–cadmium alloys. Also used for ternary lead–cadmium–antimony. The lead-rich matrix is grey, the compound SbCd blue, the antimony-rich solid solution whitish yellow, and the cadmium-rich solid solution brownish yellow. This reagent may be used hot (up to 80 °C). (Beware of recrystallization!)
7	Hydrochloric acid 10 ml Nitric acid 5 ml Alcohol 85 ml	Used for eutectic lead–tin alloys
8	Hydrochloric acid 30 ml Ferric chloride 10 g Water to 150 ml	Used mostly for lead–antimony alloys
9	Hydrochloric acid, (1.19)	General reagent for grain boundary etching. Usually good for alloys containing antimony
10	Hydrochloric acid, 1–5% in alcohol	Used for lead–tin alloys. For higher tin contents the 5% reagent is preferable
11	Nitric acid, 5% in alcohol	Produces grain contrast in lead-rich alloys
12	Nitric acid, 10% in water	Used for lead-rich alloys. May be improved by the addition of a little chromic acid
13	Sodium hydroxide saturated in water	Used for lead–tin alloys
14	Silver nitrate, 5–10% in water	Swab etch used for lead–tin and lead–antimony alloys. Useful for antifriction alloys in general
15	Molybdic acid 100 g Ammonium hydroxide 140 ml Water 240 ml Filter solution and add to nitric acid 60 ml	This reagent, applied by the alternate swab and wash technique, gives a rapid etching which is very effective for removing thick layers of cold-worked metal. It may be followed by Reagent 5 An alternative is Russell's reagent (*see* Table 10.1)
16	Citric acid 25 g Ammonium molybdate 10 g Water 100 ml	A useful grain boundary etch for lead and dilute lead alloys. Often used after chemical polish

* Acids are concentrated, unless otherwise indicated.

10.3.12 Magnesium

PREPARATION

1. Magnesium is soft and readily forms mechanical twins and so deformed layers should be avoided.
2. Abrasives and polishing media tend to become embedded. Therefore use papers well-covered with paraffin making sure the deformed layer is removed.
3. Some phases in magnesium alloys are attacked by water. If these are present use paraffin or ethanol as lubricant.
4. Some very hard intermetallics can be present. Therefore keep polishing times short to avoid relief.

The recommended procedure is to grind carefully to 600-grit silicon carbide papers. Then polish with fine α-alumina slurry or 4–6 μm diamond paste. This is followed by polishing on a fine cloth using light magnesia paste made with distilled water or a chemical attack polish of 1 g MgO, 20 ml ammon. tartrate soln. (10%) in 120 ml of distilled water. In reactive alloys, white spirit replaces distilled water and chemical attack methods avoided.

ETCHING

The general grain structure is revealed by examination under cross-polars. This will also detect mechanical twins formed during preparation. A selection of etching reagents suitable for magnesium and its alloys is given in Table 10.21. Of these, 4 and 1 are the most generally useful reagents for cast alloys, while 16 is a useful macro-etchant and, followed by 4, is invaluable for showing up the grain structure in wrought alloys.

The appearance of constituents after etching. The micrographic appearances of the commonly occurring microconstituents in cast alloys are as given in Table 10.22.

Table 10.21 ETCHING REAGENTS FOR MAGNESIUM AND ITS ALLOYS

No.	*Etchant*		*Remarks*
1	Nitric acid Diethylene glycol Distilled water	1 ml 75 ml 24 ml	This reagent is recommended for general use, particularly with cast, die-cast and aged alloys. Specimens are immersed for 10–15 s, and washed with hot distilled water. The appearance of common constituents following this treatment is outlined in Table 10.22. Mg–RE and Mg–Th alloys also
2	Nitric acid Glacial acetic acid Water Diethylene glycol	1 ml 20 ml 19 ml 60 ml	Recommended for solution-heat-treated castings, and wrought alloys. Grain boundaries are revealed. The proportions are somewhat critical. Use 1–10 s
3	Citric acid Water	5 g 95 ml	This reagent reveals grain boundaries, and should be applied by swabbing. Polarized light is an alternative
4	Nitric acid, 2% in alcohol		A generally useful reagent
5	Nitric acid, 8% in alcohol		Etching time 4–6 s. Recommended for cast, extruded and rolled magnesium–manganese alloys
6	Nitric acid, 4% in alcohol		Used for magnesium-rich alloys containing other phases, which are coloured light to dark brown
7	Nitric acid, 5% in water		Etching time 1–3 s. Recommended for cast and forged alloys containing approximately 9% of aluminium
8	Oxalic acid 20 g l^{-1} in water		Etching time 6–10 s. Used also for extruded magnesium–manganese alloys
9	Acetic acid, 10% in water		Etching time 3–4 s. Used for magnesium–aluminium alloys with 3% of aluminium

Table 10.21 ETCHING REAGENTS FOR MAGNESIUM AND ITS ALLOYS – *continued*

No.	*Etchant*	*Remarks*
10	Tartaric acid 20 g l^{-1} of water	Etching time 6 s } These reagents are recommended for magnesium-aluminium alloys with 3 to 6% of aluminium
11	Orthophosphoric acid, 13% in glycerol	Etching time 12 s }
12	Tartaric acid 100 g l^{-1} of water	Used for wrought alloys. Mg_2Si is roughened and pitted. 10 s to 2 min for Mg-Mn-Al-Zn alloys. Grain contrast in cast alloys
13	Citric acid and nitric acid in glycerol	Used for magnesium-zirconium alloys. The magnesium-rich matrix is darkened and the other phases left white
14	Orthophosphoric acid 0.7 ml Picric acid 4 g Ethyl alcohol 100 ml	Recommended for solution-heat-treated castings. The specimen is lightly swabbed, or immersed with agitation for 10–20 s. The magnesium-rich matrix is darkened, and other phases (except Mg_2Sn) are little affected. The maximum contrast between the matrix and $Mg_{17}Al_{12}$ is developed. The darkening of the matrix is due to the development of a film, which must not be harmed by careless drying
15	Picric acid saturated in 95% alcohol 10 ml Glacial acetic acid 1 ml	A grain boundary etching reagent; especially for Dow metal (Al 3% Zn 1%, Mn 0.3%). Reveals cold work and twins
16	Picric acid, 5% in ethyl alcohol 50 ml Glacial acetic acid 20 ml Distilled water 20 ml	Useful for magnesium-aluminium-zinc alloys. On etching for 15 s an amorphous film is produced on the polished surface. When dry, the film cracks parallel to the trace of the basal plane in each grain. The reagent may be used to reveal changes of composition within grains, and other special purposes
17	Picric acid, 5% in ethyl alcohol 50 ml Glacial acetic acid 16 ml Distilled water 20 ml	As for Reagent 16, but suitable for a more restricted range of alloy composition[86]
18	Picric acid, 5% in ethyl alcohol 100 ml Glacial acetic acid 5 ml Nitric acid (1.40) 3 ml	General reagent[86]
19	Picric acid, 5% in ethyl alcohol 10 ml Distilled water 10 ml	Mg_2Si is coloured dark blue and manganese-bearing constituents are left unaffected[86]
20	Hydrofluoric acid (40%) 10 ml Distilled water 90 ml	Useful for magnesium-aluminium-zinc alloys. $Mg_{17}Al_{12}$ is darkened, and $Mg_3Al_2Zn_3$ is left unetched. If the specimen is now immersed in dilute picric acid solution (1 vol. of 5% picric acid in alcohol and 9 vol. of water) the matrix turns yellow, and the ternary compound remains white[86]
21	Picric acid, 5% in ethyl alcohol 100 ml Distilled water 10 ml Glacial acetic acid 5 ml	Reveals grain-boundaries in both cast and wrought alloys. This reagent is useful for differentiating between grains of different orientations, and for revealing internally stressed regions[86]
22	Nitric acid conc.	Recommended for pure metal only. Specimen is immersed in the cold acid. After 1 min a copious evolution of NO_2 occurs, and then almost ceases. At the end of the violent stage, the specimen is removed, washed and dried. Surfaces of very high reflectivity result, and grain boundaries are revealed

ELECTROLYTIC ETCHING OF MAGNESIUM ALLOYS

This has been recommended for forged alloys. The specimen is anodically treated in 10% aqueous sodium hydroxide containing 0.06 g l^{-1} of copper. A copper cathode is used, and a current density

of 0.53 A dm^{-2} is applied at 4 V. After etching, the specimen is successively washed with 5% sodium hydroxide, distilled water and alcohol, and is finally dried.

NON-METALLIC INCLUSIONS IN MAGNESIUM-BASE ALLOYS[87,88]

The detection and identification of accidental flux and other inclusions in magnesium alloys involves the exposure of a prepared surface to controlled conditions of humidity, when corrosion occurs at the site of certain inclusions, others being comparatively unaffected. The corrosion product or the inclusion may then be examined by microchemical techniques.

The surface to be examined should be carefully machined and polished by standard procedures. The polishing time should be short, and alcohol or other solvent capable of dissolving flux must be avoided. As soon as possible the prepared specimens are placed in a humidity chamber, having been protected in transit by wrapping in paper. A suitable degree of humidity is provided by the

Table 10.22 THE MICROGRAPHIC APPEARANCE OF CONSTITUENTS OF MAGNESIUM ALLOYS

Microconstituent	*Appearance in polished sections, etched with Reagent 1 (zirconium-free alloys)*
$Mg_{17}Al_{12}$[1]	White, sharply outlined and brought into definite relief
$MgZn_2$[2]	Appearance very similar to that of $Mg_{17}Al_{12}$
$Mg_3Al_2Zn_3$[3]	Appearance similar to those of $Mg_{17}Al_{12}$ and $MgZn_2$
Mg_2Si[4]	Watery blue green; the phase usually has a characteristic Chinese-script formation, but may appear in massive particles. Relief less than for manganese
Mg_2Sn[4]	Tan to brown or dark blue, depending on duration of etching. Individual particles may differ in colour
Manganese[5]	Grey particles, usually rounded and in relief. Little affected by etching
(MgMnAl)[5]	Grey particles, angular in shape and in relief. Little affected by etching
Microconstituent	*Appearance in polished sections etched with Reagent 4 (zirconium-bearing alloys)*
Primary Zr (undissolved in molten alloy)	Hard, coarse, pinkish grey rounded particles, readily visible before etching
Zinc-rich particles[6]	Fine, dark particles, loosely clustered and comparatively inconspicuous before etching
Mg_9Ce	Compound or divorced eutectic in grain boundaries. Appearance hardly changed by few per cent of zinc or silver
Mg_3Th	Compound or divorced eutectic in grain boundaries (bluish). Appearance hardly changed by few per cent of zinc if Zn exceeds Th
(?) Mg–Th–Zn	Brown acicular phase. Appears in Mg–Th–Zn–Zr alloys when Th $\geqslant$ Zn
$MgZn_2$	Compound or divorced eutectic in grain boundaries. Absent from alloys containing RE or Th

The superscript numbers in column 1 refer to the following notes:

[1] This is the γ-phase of the magnesium–aluminium system; it is also frequently called Mg_4Al_3 or Mg_3Al_2.
[2] Although the phase MgZn may be observed in equilibrium conditions, $MgZn_2$ is frequently encountered in cast alloys.
[3] This ternary compound occurs in alloys based on the ternary system magnesium–aluminium–zinc, and may be associated with $Mg_{17}Al_{12}$.
[4] Blue unetched.
[5] These constituents are best observed in the unetched condition.
[6] Alloys of zirconium with interfering elements such as Fe, Al, Si, N and H, separating as a Zr-rich precipitate in the liquid alloy. Co-precipitation of various impurities makes the particles of indefinite composition.

Note: The microstructure of all zirconium-bearing cast alloys with satisfactory dissolved zirconium content is characterised by Zr-rich coring in the centre of most grains. In the wrought alloys zirconium is precipitated from the cored areas during preheating or working, resulting in longitudinal striations of fine precipitate which become visible on etching.

For descriptions of the metallography of magnesium alloys refs. 83–85 should be consulted.

air above a saturated solution of sodium thiosulphate. The presence of corrosive inclusions is indicated by the development of corrosion spots. At this stage the corroded area may be lightly ground away to expose the underlying structure for microexamination so that the micrographic features which are holding the flux become visible. With other specimens, or with the same specimens re-exposed to the humid conditions, identification of the inclusions may be proceeded with, as follows:

1. *Detection of chloride*

The corrosion product is scraped off, and dissolved on a microscope slip in 5% aqueous nitric acid. A 1% silver nitrate solution is then added, and a turbidity of silver chloride indicates the presence of the chloride ion. The solution of the corrosion product should preferably be heated before adding the silver nitrate to remove any sulphide ion, which also gives rise to turbidity. Alternatively, a 10% solution of chromium trioxide may be added directly to the corrosion spot, when chloride is indicated by an evolution of gas bubbles from the metal surface, and the development of a brown stain. This method is less specific than the silver nitrate method, and may give positive reactions in the presence of relatively large amounts of sulphates and nitrates.

2. *Detection of calcium*

Scrapings of corrosion product are dissolved in a small watch glass on a hot plate in 2 ml water and one drop of glacial acetic acid. To the hot solution a few drops of saturated ammonium oxalate solution are added. The presence of calcium is indicated by turbidity or precipitation. Spectroscopic identification of calcium in the solution is also possible.

3. *Detection of boric acid in inclusions*

Scrapings of corrosion product and metal are placed in a test tube with 1 ml of water. The inclusion dissolves, and complete solution of the sample is effected by adding a small portion of sulphuric acid (density 1.84) from 9 ml carefully measured and contained in a graduated cylinder. When solution is complete, the remainder of the acid is added and the mixture is well shaken; 0.5 ml of a 0.1% solution of quinalizarin in 93% (by wt.) of sulphuric acid is now added, mixed in, and allowed to stand for 5 min. A blue colour indicates the presence of boric acid. The colour in the absence of boric acid varies from bluish violet to red according to the dilution of the acid, which must thus be carefully controlled as described.

4. *Detection of nitride*

A drop of Nessler's solution applied directly to the metal surface in the presence of nitride, gives an orange brown precipitate, which may take about 1 min to develop. This test should be made on freshly prepared surfaces on which no water has been used, since decomposition of nitride to oxide occurs in damp air.

5. *Detection of sulphide*

The corrosion product is added to a few drops of water slightly acidified with nitric acid. A drop of the solution placed on a silver surface gives rise to a dark stain if sulphide was present in the corrosion product. Sulphur printing may also be applied.

6. *Detection of iron*

The corrosion product is dissolved in hydrochloric acid. A drop of nitric acid is added with several drops of distilled water. In the presence of iron, the addition of a crystal of ammonium thiocyanate develops a blood-red colouration.

In all the above tests, a simultaneous *blank* test should be carried out.

Iron-printing, analogous to sulphur-printing, can be applied using cleaned photographic paper impregnated with a freshly prepared solution of potassium ferricyanide and potassium ferrocyanide acidified with nitric or hydrochloric acid.

10.3.13 Molybdenum

PREPARATION

Normal methods are used but it is difficult to obtain a scratch-free underformed surface and it is preferred to use attack polishing. This requires a fine α or γ alumina slurry with 1 g potass. ferricyanide, 0.5 g sod. hydroxide, 100 ml water.

ETCHING

Etchant	*Conditions*	*Remarks*
1. (a) Potass. hydroxide 10 g Water to 100 ml (b) Pot. ferricyanide 10 g Water to 100 ml	Mix equal amounts of (a) and (b) as needed	Grain boundary etch
2. Ammonia (0.88) 50 ml Hydrogen peroxide (3%) 50 ml Water 50 ml	Boil for up to 10 min	General etch

10.3.14 Nickel

PREPARATION

Great care must be taken to produce polishes of a high quality, with as little deformation as possible at the surface, since it is difficult to remove much surface material from nickel during etching.

ETCHING

Since nickel is generally resistant to corrosive media, etching involves the use of vigorous reagents, which tend to form etch pits and to dissolve out inclusions. The difficulty of etching increases with the purity of the metal, and alternate polishing and etching is frequently necessary. In general, etching reagents (Table 10.23) produce grain boundary effects without much grain contrast. Low nickel copper–nickel alloys may be etched by the reagents recommended for the purpose under *Copper*. Heat-resisting nickel-base alloys are etched with the solutions used for stainless steels (Table 10.18).

Table 10.23 ETCHING REAGENTS FOR NICKEL AND ITS ALLOYS

No.	*Etchant*	*Remarks*
1	Nitric acid (1.40) 10 ml Hydrochloric acid (1.19) 20 ml Glycerol 30 ml	Pure nickel, and nickel-chromium alloys. Grain boundaries etched
2	Nitric acid (1.40) 10 ml Acetic acid 10 ml Acetone 10 ml	Used for pure nickel, cupro-nickel, Monel metal and nickel-silver
3	Nitric acid (1.40) 50 ml Glacial acetic acid 25 ml Water 25 ml	Useful for nickel and most nickel-rich alloys
4	Nitric acid, 2% in alcohol, mixed in various proportions with hydrochloric acid, 2% in alcohol	Used for pure nickel
5	Hydrochloric acid 30 ml Ferric chloride 10 g Water 120 ml	Pure nickel
6	Hydrochloric acid (1.19) 20 ml Ferric chloride 10 g Water 30 ml	Pure nickel

Table 10.23 ETCHING REAGENTS FOR NICKEL AND ITS ALLOYS —*continued*

No.	*Etchant*	*Remarks*
7	Sulphuric acid (1.84) 1 ml Hydrogen peroxide (10%) 10 ml	Pure nickel
8	Sulphuric acid (1.84) 10 ml Potassium dichromate (saturated in water) 50 ml	Pure nickel
9	Ammonium persulphate 100 $g l^{-1}$ of water	Cast nickel
10	Ammonium per sulphate, 10% in water 10 ml Potassium cyanide, 10% in water 10 ml	Pure nickel. Also recommended for cross-sections of nickel plated steels. The steel is not affected but may be etched by Reagent 2 for *Iron and steel*
11	Ammonium hydroxide	Used as a polish attack for nickel plate
12	Ammonium hydroxide 85 ml Hydrogen peroxide 30% 15 ml	Used for nickel-silvers

ELECTROLYTIC ETCHING OF NICKEL AND ITS ALLOYS

This technique frequently gives better results than ordinary immersion or swab etching. Suitable solutions are summarized in Table 10.24.

Table 10.24 ELECTROLYTIC ETCHING OF NICKEL ALLOYS

No.	*Etchant*	*Conditions*	*Remarks*
1	Sulphuric acid (1.84) 22 ml Hydrogen peroxide (30%) 12 ml Water to 100 ml	6 V d.c. Pt cathode 5–30 s	General etch
2	Sulphuric acid (1.84) 5 ml Water to 100 ml	6 V d.c. Pt cathode 5–15 s	All Ni–base alloys, especially Ni–Cu and Ni–Cr. Delineates carbides
3	Ammon. persulphate 10 g Water to 100 ml	6 V d.c. Nickel cathode	Most alloys, especially Ni–Fe Ni–Cr cast alloys
4	Chromium trioxide 6 g Water to 100 ml	As etchant 3	As etchant 3
5	Nitric acid (1.40) 10 ml Glacial acetic acid 5 ml Water 85 ml	1.5 V d.c. Pt cathode 20–60 s (*do not keep*)	Grain contrast for all nickel alloys
6	Oxalic acid 10 g Water 100 ml	6 V d.c. Stainless steel cathode 10–15 s	Superalloys, Ni–Au, Ni–Cr, Ni–Mo alloys

Table 10.24 ELECTROLYTIC ETCHING OF NICKEL ALLOYS—*continued*

No.	*Etchant*		*Conditions*	*Remarks*
7	Phosphoric acid (1.71)	70 ml	2–10 V d.c. Ni cathode	Superalloys (Nimonics) Ni–Cr, Ni–Fe
	Water	30 ml	5–60 s	
	(if necessary, sulphuric acid (1.84))	15 ml		
8	Phosphoric acid (1.71)	85 ml	10 V d.c. Pt cathode	Ni–base superalloys. Gamma prime paper Ti and Nb segregation
	Sulphuric acid (1.84)	5 ml	5–30 s	
	Chromium trioxide	8 g		

10.3.15 Niobium

PREPARATION

Niobium is soft and tough but can be prepared by methods used for stainless steel. It is best polished using a polish attack method on an acid-resistant cloth using gamma alumina and a solution of:

Hydrofluoric acid	2 ml
Nitric acid	5 ml
Lactic acid	30 ml

This is slow (approx. 1 hour) and needs an automatic polisher as the solution is very corrosive.

Table 10.25 ETCHING REAGENTS FOR NIOBIUM ALLOYS

No.	*Etchant*		*Conditions*	*Remarks*
1	Hydrochloric acid (1.19)	15 ml	Immerse 10–60 s	The only general-purpose etch free from HF
	Sulphuric acid (1.84)	15 ml		
	Nitric acid (1.40)	8 ml		
	Water	62 ml		
2	Hydrofluoric acid (40%)	10 ml	Immerse 15–20 s	General etch
	Nitric acid (1.40)	10 ml		
	Lactic acid	30 ml		
3	Hydrofluoric acid (40%)	10 ml	Immerse up to 3 min *or*	Grain boundary etch, especially at low voltages, electrolytically
	Nitric acid (1.40)	20 ml	Use electrolytically 12–30 V d.c.	
	Water	70 ml	Pt cathode up to 1 min	

10.3.16 Platinum group metals

PREPARATION

On polishing platinum and many of its analogues, considerable surface flow may occur, and this makes the subsequent etching operations difficult to control, and gives a poor appearance to the microstructure.

ETCHING

The reagents given in Table 10.25 will produce satisfactory microstructures if the preparation and polishing have been carefully done. However, owing to the almost invariable presence of a flowed layer after mechanical polishing, it is frequently recommended that electrolytic etching be used.

Table 10.26 ETCHING REAGENTS FOR PLATINUM GROUP

No.	*Etchant*		*Conditions*	*Remarks*
1	Aqua Regia			
	Nitric acid (1.4)	34 ml	Up to 1 min. May need to be warmed	Pt, Pd, Rh alloys
	Hydrochloric acid (1.19)	66 ml		
2	Potass. ferricyanide	3.5 g	Several minutes	Most alloys, including Os alloys.
	Sod. hydroxide	1 g		
	Water	150 ml		
3	Hydrochloric acid (1.19)	20 ml	Several minutes	Ru alloys.
	Hydrogen peroxide (3%)	1 ml		
	Water	80 ml		
4	Potass. cyanide	5 g	Electrolytic	Pt. alloys.
	Water	100 ml	1–5 V a.c. Pt cathode 1–2 min	
5	Hydrochloric acid (1.19)	20 ml	Electrolytic with Pt or graphite	
	Sod. chloride	25 g	electrode.	
	Water	65 ml	25 s 10 V a.c.	Rh alloys
			1 min 1.5 V a.c.	Pt–Rh alloys
			1–2 min 20 V a.c.	Ir alloys
			1 min 6 V a.c.	Pt alloys
			1 min 5–20 V a.c.	Ru-base alloys
6	Hydrochloric acid (1.19)	10 ml	Electrolytic 30 s, 10 V a.c.	Os, Pd, Pt, Ir.
	Ethanol	90 ml	Graphite cathode	
7	Hydrochloric acid (1.19)		1–2 min electrolytic 5 V a.c. Pt or graphite electrode	Rh, Pt. Grain contrast

10.3.17 Silicon

PREPARATION

Lump silicon, which is very hard and brittle, may be prepared for metallographic examination by methods similar to those recommended for hard alloys. No standard procedure appears to have been developed. Both electrolytic polishing and chemical polishing have met with some

success (*see* Tables 10.4b and 10.4). Coarse abrasives leave rows of pits and so it is preferred to use fine silicon carbide papers where possible.

ETCHING

Polished surfaces of silicon may be etched with 5% aqueous hydrofluoric acid, to which various amounts of concentrated nitric acid may be added. Microstructures developed in this way show angular grains, with twin markings, together with the particles of other constituents due to the presence of impurities (e.g. iron, aluminium and calcium). The precise nature of the impurity particles is not clear.

Commercial silicon may contain inclusions of slag and unreduced quartz. Silicate inclusions may be detected by etching a polished section for 3 h in a stream of chlorine. The specimen is then immersed in concentrated hydrofluoric acid for 10 min in order to etch and attack the quartz inclusions (*see also* Table 10.9, p. 10–21).

10.3.18 Silver

PREPARATION

Silver is comparatively soft, so that extreme care and cleanliness must be maintained. Otherwise normal methods of preparation are suitable. In polishing, proprietary metal polishing media containing ammonia or ammoniacal compounds should be avoided.

Table 10.27 ETCHING REAGENTS FOR SILVER AND ITS ALLOYS

No.	*Etchant*	*Remarks*
1	Ammonium hydroxide and hydrogen peroxide—various proportions	The silver-rich matrix is in general unaffected. Other phases (e.g. the β silver–antimony phase) are often coloured blue to brown
2	Ammonium hydroxide 50 ml Hydrogen peroxide (3%) 10–30 ml	Recommended for silver, silver–nickel and silver–palladium alloys. Also useful for the examination of silver-soldered joints
3	Sulphuric acid (10% in water) to which a few crystals of chromic acid CrO_3 have been added (2 g)	This reagent reveals the grain structure of silver and silver-rich alloys
4	Solution containing 7.6 g l^{-1} of chromic acid CrO_3 and 8 g l^{-1} of sulphuric acid	Useful general etching reagent. Used as a sensitive etching reagent for silver–copper alloys
5	Ferric chloride 20 g l^{-1} of water	Recommended for silver solders
6	Potassium cyanide, 10% in water 10 ml Ammonium persulphate, 10% in water 10 ml	Etch for pure silver and dilute alloys. Duration 1–2 min
7	Solution A: 50 : 50 nitric acid in water 100 ml Potassium dichromate 2 g Solution B: Chromic acid CrO_3 20 g Sodium sulphate 1.5 g Water 100 ml	Used for silver alloys in general. Solution A is diluted to 20 vol. and an equal amount of solution B added. The reagent is applied by gentle swabbing or with a camel hair brush. A loose film of silver chromate should form if the reagent is working correctly. If the film is adherent, more of solution A should be added. If no film forms, more of solution B is required
8	Chromic acid, CrO_3, 0.2% and sulphuric acid, 0.2% in water	Used (1 min immersion) for silver and silver-rich alloys
9	Potassium dichromate saturated in water 100 ml Sodium chloride saturated in water 2 ml Sulphuric acid 10 ml	Silver and silver-rich alloys Silver solders

Table 10.27 ETCHING REAGENTS FOR SILVER AND ITS ALLOYS—*continued*

No.	*Etchant*		*Remarks*	
10	Chromic acid and hydrogen peroxide in water. Various proportions		General reagent. Composition adjustments must be made to suit specific cases	
11	Sodium hydroxide (10%) Potass. ferricyanide (30%)	10 ml 10 ml	5–15 s (dilute with equal vol. of water if too fast)	Ag alloys with W, Mo and WC

Pure silver and dilute silver alloys are difficult to etch, but several solutions will give good results on duplex or more complex alloys. The strengths of the reagents, unless otherwise noted in Table 10.27, should be adjusted to the specific alloys to be examined.

ELECTROLYTIC ETCHING OF SILVER

In many cases excellent grain boundary and grain contrast etching is obtained by electrolysis (specimen as anode) in one of the following solutions:

Table 10.28 ELECTROLYTIC ETCHING OF SILVER ALLOYS

No.	*Etchant*	*Remarks*
1	Citric acid 100 g l^{-1} of water	15 s to 1 min. 6 V d.c. Ag cathode. Most alloys
2	Ammoniacal ammonium molybdate	Molybdic acid is dissolved in an excess of strong ammonia. The composition is not critical provided ammonia is in excess. The optimum potential and current density should be experimentally established for each case
3	Potassium cyanide 50 g l^{-1} of water	This reagent is used particularly for silver when it is in contact with other metals, as in plated articles. Optimum conditions should again be established experimentally
4	Hydrofluoric acid + a little stannous chloride	Used for silver–tin alloys containing more than 73% of silver

See also reagents listed for electrolytic polishing of silver, Table 10.4b. The silver cyanide–potassium cyanide–potassium carbonate reagent in Table 10.4b is particularly convenient, since, on reduction of the polishing potential from 1.5 to 0.5 V for 90 s, etching occurs.

10.3.19 Tantalum

PREPARATION

For the preparation of tantalum (pure and commercial) it is recommended that polishing should be carried out on felt (5–10 min), using the following mixture as polishing medium:

Alumina, carefully levigated	35 g
Hydrofluoric acid (60%)	20 ml
Ammonium fluoride	20 g
Distilled water	1 000 ml

See also Niobium.

ETCHING

The reagents given in Table 10.29 have been found useful.

Table 10.29 ETCHING REAGENTS FOR TANTALUM

No.	*Etchant*		*Remarks*
1	Ammonium fluoride, 20% in water	10 ml	Used at 50–60 °C (ineffective when cold). Immersion for 1 min etches up the structure of tantalum without colouring inclusions of tantalum sulphide, Ta_2S_3
	Hydrofluoric acid, (40%) 60% in water	10 ml	
2	Ammonium fluoride, 20% in water	10 ml	Used at 60 °C for 1–2 min. Etching effects are similar to those for Reagent 1
	Sulphuric acid (1.84)	20 ml	
3	Ammonium fluoride, 20% in water	10 ml	Used at 60 °C; the matrix is usually not adequately etched but Ta_2S_3 is blackened. This reagent may be used after Reagent 1 or 2 to identify Ta_2S_3
	Nitric acid	10 ml	
4	Ammonium fluoride, 20% in water		Used for 5–6 min at 80 °C. The grain structure of the matrix is developed, and Ta_2S_3 is not affected
5	Ammonium fluoride, 20% in water	20 ml	This reagent is used boiling, and colours Ta_2S_3 brown. The matrix is not affected
	Hydrogen peroxide	10 ml	
6	Sulphuric acid	25 ml	For general structure[89]
	Nitric acid	10 ml	
	Hydrofluoric acid	10 ml	

10.3.20 Tin

PREPARATION

Because of its relative softness, the same precautions should be observed as for lead and its alloys. Very careful hand-grinding is necessary in order to avoid surface recrystallization, and again the microtome technique (*see Lead*) may be used with advantage. The flowed layer on the surface may be removed before the final etching treatment by immersion in 10–20% aqueous hydrochloric acid. The technique involving alternate polishing and etching very frequently proves advantageous. If specimens are mounted for metallographic preparation, care should be used, since tin is liable to flow under the pressures necessary for the usual mounting processes.

For further details of methods for tin and tin alloys, refs. 1, 2, 91 and 92 may be consulted.

ETCHING

Tin is anisotropic and the grain structure can be revealed under crossed-polars. The reagents of Table 10.30 have been recommended for tin-rich alloys. In general, etching times are not critical, and the progress of the treatment should be judged visually.

Table 10.30 ETCHING REAGENTS FOR TIN AND ITS ALLOYS

No	*Etchant**		*Remarks*
1	Nitric acid, 2% in alcohol		This reagent is a general one for tin-rich alloys, and particularly for tin–cadmium, tin–antimony and tin–iron alloys. The tin-rich matrix is darkened, and the intermetallic compounds usually little affected
2	Nitric acid, 5% in alcohol		Tin, tin–cadmium and tin–iron alloys
3	Nitric acid	10 ml	Mainly used as a reagent for tin. Used at 38–40 °C
	Acetic acid	30 ml	
	Glycerol	50 ml	

* Acids are concentrated, unless otherwise indicated

Table 10.30 ETCHING REAGENTS FOR TIN AND ITS ALLOYS —*continued*

No.	*Etchant**	*Remarks*
4	Nitric acid 10 ml Acetic acid 10 ml Glycerol 80 ml	Used, at 38–40 °C, for tin–lead alloys, especially tin-rich alloys. Pb is blackened.
5	Picric acid and nitric acid in alcohol—proportions variable	Useful for tin–iron alloys in contact with steel.
6	Hydrochloric acid, 1–5% in alcohol	Useful for tin–lead, tin–cadmium, tin–iron, tin–antimony–copper alloys.
7	Hydrochloric acid 2 ml Ferric chloride 10 g Water 95 ml	Useful for tin-rich alloys in general and for Babbitt metal. It is often an advantage to add alcohol to this reagent. Any cadmium-rich solid solution present is stained black, while the β-phase of the tin–cadmium system turns brown
8	Hydrochloric acid 5 ml Ferric chloride 2 g Water 30 ml Alcohol 60 ml	Reveals general structure of tin and alloys without lead. Tin–iron and tin–copper compounds unattacked
9	Stannous chloride in acid solution	Tin-rich alloys in general. The composition may be varied to suit individual alloy systems
10	Potassium dichromate, in dilute acidified aqueous solution (composition variable)	Recommended for tin–cadmium alloys
11	Potassium ferricyanide in caustic soda (composition variable)	Used for tin–cadmium–antimony alloys. It distinguishes SbSn (with tin and cadmium in solid solution), which is not affected, from CdSb in tin–cadmium–antimony alloys
12	Ammonium persulphate 5–10 g Water 100 ml	Used particularly for tinplate. The tin is heavily darkened, leaving the basis metal unattacked. Most intermetallic compounds of tin are also unattacked. More dilute solution gives grain boundary etch with tin and alloys
13	Nitric acid and hydrofluoric acid in glycerol	Various strengths are recommended for tinplate. The contrast between plating and steel may be improved by the use of Reagent 2 (Table 10.17)
14	Sodium sulphide 20% in water, with a few drops of hydrochloric acid	Useful for tin-rich tin–antimony–copper alloys. The phase SbSn is not affected, but the phase Cu_6Sn_5 is coloured brown[93]
15	Silver nitrate 5 g Water 100 ml	Darkens primary and eutectic lead in lead-rich lead–tin alloys[91]

* Acids are concentrated, unless otherwise indicated.

ELECTROLYTIC ETCHING OF TIN ALLOYS

A 10% aqueous solution of hydrochloric acid or 20% sulphuric acid may be used at a very low current density; this is especially useful for tin–iron alloys. Satisfactory results are also obtained from:

Glacial acetic acid	130 ml
Perchloric acid	50 ml

used at a current density of 3–6 A dm^{-2}. (Take care; *see* Section 10.2, p. 10–8, *Electrolytic polishing*).

10.3.21 Titanium

PREPARATION

The preparation of titanium samples by ordinary methods of grinding is straightforward but needs care; final polishing is difficult. Specimens are easily scratched, and mechanical working of the surface during polishing causes twin-formation which may obscure other metallographic features.

Other 'false' structures may be caused by the presence of local, randomly dispersed areas of cold work, which give a duplex appearance to homogeneous specimens. Electrolytic polishing of surfaces ground wet by ordinary methods to the 000 grade of emery paper is therefore recommended[95] (*see* Table 10.4b).

Mechanical polishing, if preferred, may be carried out with diamond preparation, with a final fine polish (if required) with alumina, both with a trace of hydrofluoric acid.

Examination for hydride is carried out in polarised light between crossed polaroids; the hydride then appears bright and anisotropic. This also reveals the grain structure of α-titanium.

ETCHING

The presence of surface oxide films on titanium and its alloys necessitates the use of strongly acid etchants. Those given in Table 10.31 are useful.

Table 10.31 ETCHING REAGENTS FOR TITANIUM AND ITS ALLOYS

No.	*Etchant*		*Conditions*	*Remarks*
1	Hydrofluoric acid (40%)	1–3 ml	5–30 s	Mainly unalloyed titanium; reveals hydrides
	Nitric acid (1.40)	10 ml		
	Lactic acid	30 ml		
2	Hydrofluoric acid (40%)	1 ml	5–30 s	As Etchant 1
	Nitric acid (1.40)	30 ml		
	Lactic acid	30 ml		
3	Hydrofluoric acid (40%)	1–3 ml	3–10 s	Most useful general etch
	Nitric acid (1.40)	2–6 ml		
	Water	to 100 ml		
	(Kroll's reagent)			
4	Hydrofluoric acid (40%)	10 ml	5–30 s	Chemical polish and g.b. etch
	Nitric acid (1.40)	10 ml		
	Lactic acid	30 ml		
5	Potassium hydroxide (40%)	10 ml	3–20 s	Useful for α/β alloys. α is attacked or stained. β unattacked
	Hydrogen peroxide (30%)	5 ml		
	Water	20 ml		
	(can be varied to suit alloy)			
6	Hydrofluoric acid (40%)	20 ml	5–15 s	General purpose, TiAlSn alloys
	Nitric acid	20 ml		
	Glycerol	40 ml		
7	Hydrofluoric acid	1 ml	3–20 s	TiAlSn alloys
	Nitric acid (1.40)	25 ml		
	Glycerol	45 ml		
	Water	20 ml		

10.3.22 Tungsten

PREPARATION

Specimens, which are extremely hard, must be ground flat on an emery or carborundum wheel. Fine grinding may be carried out in the usual manner, and polishing, which is relatively easy, is done with graded alumina suspensions. In view of the difficulty of etching (*see* below) it has been recommended that tungsten should be prepared by a polish attack.[97] The specimen may be taken

directly from the No. 0 emery paper to a polishing wheel which is moistened with a cold suspension of the polishing medium in an etching reagent (e.g. 3.5 g of potassium ferrocyanide and 1 g of caustic soda in 150 ml distilled water) and polished for approximately 15 s. After rinsing, the specimen is dipped in the etching reagent alone for 5 s, and is again rinsed and dried. This process results in considerable saving of time. Many commercial tungsten products are in the form of small complex shapes, fine wires and filaments, and this raises special problems in mounting for metallographic examination. It is recommended that small complicated specimens should be embedded in a low melting point glass which has been melted into a groove or cavity in a metal holder. The composite sample may then be ground and polished in the usual manner to expose the section required. Ordinary mounting agents are too soft for satisfactory use with tungsten. A suitable glass may be prepared by fusing 85 g of lead peroxide with 15 g of boric acid. This may be darkened by a little manganese dioxide, and melts at approximately 450 °C.

ETCHING

The etching of tungsten is difficult, but Murakami's etch is most often used. Inclusions (e.g. thorium, uranium or calcium oxides) may be seen in the polished, unetched surface, while the general structure of filaments which have been heated *in vacuo* or in a reducing atmosphere may often be observed owing to evaporation effects. A selection of suitable etching reagents is given in Table 10.32.

ELECTROLYTIC ETCHING OF TUNGSTEN

This may be carried out in a mixture of 25 ml of normal aqueous sodium hydroxide and 20 ml of hydrogen peroxide. The current density and potential are somewhat critical, and should be carefully controlled after investigation to find the optimum conditions for specific cases.

Sodium hydroxide solution of 0.025 normal strength has also been used, at a current density of 5 A dm^{-2}.

Table 10.32 ETCHING REAGENTS FOR TUNGSTEN

No.	*Etchant*		*Remarks*
1	Sodium hydroxide, 10% in water	10 ml	This reagent is used cold and, on immersion of the specimen for approximately 10 s, develops grain boundaries (Murakami's reagent)
	Potassium ferricyanide, 10% in water	10 ml	
2	Hydrogen peroxide, 3% in water		This reagent develops grain boundaries, but only after some 30–90 s in the boiling reagent
3	Potassium ferricyanide	305 g	Recommended for deep etching of single crystal bars and wires in order to produce etch-pits for the investigation of orientation
	Caustic soda	44.5 g	
	Water	1 000 ml	
4	Hydrofluoric acid	5 ml	Swab 10–20 s, rinse and dry. Follow with Murakami's reagent (Etchant 1)
	Nitric acid (1.40)	10 ml	
	Lactic acid	30 ml	

10.3.23 Uranium

PREPARATION

Conventional methods are used but as the metal is toxic, pyrophoric when finely divided, and an α-particle emitter, it is essential to keep the metal wet during cutting and to carry out the operation behind a screen so that particles cannot be ingested.

Final polishing may be carried out with magnesia or alumina on Selvyt or terylene cloth.

Chromium oxide (green) is also used but tends to smear the structure and pull out inclusions. Polish attack methods are preferred and give structures which can be examined under polarized light with crossed polars, which is the most useful method of examination.[43]

Polish attack solutions are:

1. Dilute hydrofluoric acid and nitric acid (1 ml + 5 ml respectively in 100 ml water).
2. 50 g chromium trioxide, 10 ml nitric acid, 100 ml water is less aggressive but, like the other, needs careful handling to avoid contact with the skin. This gives the best results for polarized light examination.

ETCHING

Polarized light is the most useful technique.

α uranium — high grain contrast under crossed polars about 1° off the extinction position. The various transformation products, granular α, martensites etc., can be distinguished.

β uranium — weakly anisotropic when retained but clearly distinguished from α and γ.

γ uranium — optically isotropic and therefore distinguished from α and β. In uranium alloys with molybdenum, niobium and rhenium, γ_0, tetragonal with $c/a = 0.5$ is optically active and the grain structure is visible under crossed polars.

On ageing, these alloys develop γ_0 with $c/a < 0.5$ and this is readily detected by polarized light metallography.

Note that chemical etching may give quite different structures, e.g. in U–Ti alloys. Chemical etching is responsive to the manner of decomposition of γ uranium and will reveal the sequence of decomposition, e.g. distribution of U_2Ti, UZr_2 etc., whereas polarized light reveals the final and true grain structure which may be quite different from the etched structure.[45]

Table 10.33 ETCHING REAGENTS FOR URANIUM ALLOYS

No.	*Etchant*		*Conditions*	*Remarks*
1	Nitric acid (1.40)	30 ml	5–60 s	Most U alloys; distinguishes precipitated phases, e.g U_2Ti, U_2Mo, UZr_2, eutectoid nucleation at grain boundaries (like pearlite in steel)
	Glacial acetic acid	30 ml		
	Glycerol	30 ml		
2	Orthophosphoric acid	30 ml	Electrolytic 20 V stainless steel cathode 5–30 s	Will electropolish at high voltages (30–40 V), stains phases differentially at 10–20 V
	Diethylene glycol	30 ml		
	Ethanol	40 ml		
3	Hydrofluoric acid (40%)	10 ml	5–10 s	U–Mo, U–Nb, U–Zr alloys (gamma phase)
	Nitric acid (1.40)	40 ml		
	Glycerol	40 ml		
4	Hydrofluoric acid (40%)	1 ml	5–30 s	U–Be, U–Nb, U–Zr, U–Mo. Also U–Al alloys. UAl_2, UAl_3, UAl_4 stained differentially according to time
	Nitric acid (1.40)	30 ml		
	Lactic acid (or distilled water)	30 ml		

10.3.24 Zinc

PREPARATION

Though harder than lead and tin, zinc and its alloys must be carefully prepared, since careless grinding, involving distortion of the surface, produces mechanical twinning in a comparatively thick surface layer. Owing to these deep surface effects, at least 2 mm must be removed from a sawn or filed surface, overheating being avoided, as it is likely to cause recrystallization of the

surface layers. Also, the successive grindings should be carried on past the stage at which scratches due to the previous treatment have disappeared. The depth of the deformed layer may be much greater than the deepest scratch. Coarse grained specimens of the pure metal need the most care in this respect; find grained metal, and most of the common alloys, are less liable to such deep surface distortion.

Polishing may be carried out on a slowly rotating wheel, and it is often an advantage to etch and polish alternatively, in order to avoid the production of a distorted layer during the polishing process. Since zinc alloys often contain hard particles of intermetallic compounds, this method tends to produce excessive relief in some cases, and must be used with discretion. A suitable etching reagent for this purpose is a solution containing 200 g of chromic acid (CrO_3), 15 g of anhydrous sodium sulphate and 1 000 ml of water.

Table 10.34 ETCHING REAGENTS FOR ZINC AND ITS ALLOYS

No.	*Etchant*	*Remarks*
1	Hydrochloric acid, 1% in alcohol	These reagents are of general applicability to zinc and many zinc-rich alloys. Etchant 3 is suitable for examination of microconstituents at high magnifications
2	Sodium hydroxide 100 g l^{-1} of water	
3	Nitric acid, 1–2% in alcohol	Rinse in 20% chromic acid in water to avoid stains. Good for Zn–Fe layers in galvanized samples
4	Nitric acid 94 ml, Chromic acid 6 ml } Stock solution	A few drops of this stock solution are added to 100 ml of water immediately before use. The resulting solution is generally useful, particularly for the recognition of small amounts of other micro-constituents in zinc
5	Chromic acid, CrO_3 200 g Sodium sulphate, Na_2SO_4 15 g Water 1 000 ml	General reagent for commercial zinc and zinc alloys. If a film of stain results, this may be removed by immersion in a 20% solution of chromic acid in water
6	Chromic acid, CrO_3 50 g Sodium sulphate, Na_2SO_4 4 g Water 1 000 ml	As for Etchant 5. This composition is recommended for die-castings
7	Chromic acid, CrO_3 200 g Sodium sulphate, Na_2SO_4 7.5 ml Water 1 000 ml	Recommended for zinc-rich alloys containing copper. Subsequent immersion in 20% chromic acid solution is again helpful
8	Chromic acid, CrO_3 200 g Sodium sulphate, Na_2SO_4 7 g Sodium fluoride 2 g Water 1 000 ml	Recommended for die-casting alloys containing aluminium, as the aluminium-rich microconstituent is satisfactorily etched with this reagent. In the presence of copper, staining may result; to prevent this, immerse after etching, without washing, in a solution of 50 g chromic acid and 4 g sodium sulphate in 1 000 ml water (*see* Etchant 5).
9	Solution prepared thus: mix 51 ml of concentrated potassium hydroxide solution with 50 ml of water and 20 ml of concentrated copper nitrate solution. Stir in 25 g of powdered potassium cyanide. Filter, and add 2.5 ml of concentrated citric acid solution before use	Etch by immersion for 10–20 s. The zinc-rich phase is coloured dark brown to black. The iron-phase in commercial alloys usually appears as white rods, and the lead-phase as round white spots

ETCHING

The reagents listed in Table 10.34 may be used for zinc and its alloys.

ELECTROLYTIC ETCHING OF ZINC ALLOYS

Comparatively little work has been done on electrolytic etching of zinc alloys, since the microstructures are relatively simple and adequately brought out by the above reagents. For alloys containing copper, however, a 20% aqueous chromic acid solution has been recommended, the specimen being the anode.

Ternary alloys containing aluminium and copper may be conveniently etched electrolytically in a solution made by adding 20 drops of hydrochloric acid to 50 ml alcohol.

DEVELOPMENT OF MICROSTRUCTURES WITHOUT ETCHING

Zinc and many zinc-rich alloys develop satisfactory microstructures if the polished surface is allowed to remain exposed to the air for 1–3 days. Similar results may be obtained by heating at 100 °C for a shorter time, but care must be taken to ensure that the use of the high temperature does not lead to any structural modification.

10.3.25 Zirconium

PREPARATION

In general, standard methods of preparation may be used, but difficulties may be encountered in connection with the production of twin markings by surface deformation.[104] Further hand or machine grinding on successive grades of silicon carbide papers gives good results, particularly when a considerable proportion of hard intermetallic compound is present. Alundum papers may also be used, but tend to fragment compound particles. The final polish is given on two wheels used successively. On the first wheel, diamond dust (5–8 μm) is used with kerosene on aeroplane silk, or billiard cloth if the specimen is subject to scratching. The second wheel employs synthetic sapphire with water as lubricant.

The use of plastic laps and attack polishing is also recommended (Table 10.3, p. **10**–8), while chemical polishing (Table 10.5, p. **10**–14) is often effective.

ETCHING

The etching reagents for zirconium and its alloys are summarized in Table 10.35.

Table 10.35 ETCHING REAGENTS FOR ZIRCONIUM

No.	*Etchant*		*Remarks*
1	Nitric acid (1.40)	20 ml	The reaction rate may be increased by heating the sample in a stream of hot water before immersion in the reagent. Conversely the reaction rate is decreased by chilling the specimen
	Hydrofluoric acid (1.19)	20 ml	
	Glycerol	60 ml	
2	Glycerol	60 ml	On etching for 3–5 s, microconstituents are outlined and differentiated, and carbides unattacked. In the presence of moisture the reagent tends to stain the specimen
	Hydrofluoric acid (1.19)	20 ml	
	Nitric acid	10 ml	
3	Glycerol	16 ml	Etching times of 1–2 s are used. The reagent is useful for alloys which are not satisfactorily etched by Etchant 2
	Hydrofluoric acid (1.19)	2 ml	
	Nitric acid (1.40)	1 ml	
	Water	2–4 ml	
4	Hydrofluoric acid (1.19)	20 ml	Short etching times are necessary (1–2 s). The reagent is similar to Etchant 3 but is more drastic
	Water	80 ml	
	Nitric acid (1.40)	1 ml	

ELECTROLYTIC ETCHING

Solutions for electrolytic etching are given in Table 10.36.

Table 10.36 ELECTROLYTIC ETCHING OF ZIRCONIUM

No.	*Etchant*		*Remarks*
1	Ethyl alcohol	70 ml	Suitable for cast zirconium
	Perchloric acid (density 1.2)	20 ml	
	2-Butoxy-ethanol	10 ml	
2	Acetic acid	1 000 ml	Suitable for worked and annealed material
	Perchloric acid (density 1.59)	50 ml	
3	Ethyl alcohol	30 ml	Etching time 10–20 s at 1 A dm^{-2}
	Hydrochloric acid conc.	10 ml	
4	Ethyl alcohol	450 ml	As for Etchant 3
	Distilled water	70 ml	
	Perchloric acid	25 ml	

10.3.26 Bearing metals (lead–tin–antimony), low melting solders, and type metals

PREPARATION

Bearing metals consist of hard particles of intermetallic compounds set in a matrix of soft lead-rich or tin-rich material. Much the same applies to printing metals and solders. The precautions to be observed are in general those to be observed for lead alloys and tin alloys, and a microtome may be used with advantage. Very light pressure during grinding is essential, and care must be taken, during polishing, to ensure that the soft matrix is not smeared over the surfaces of hard particles, and that the latter are not obtained in excessive relief.

ETCHING

All the reagents listed for lead and tin alloys may be tried for revealing the structure of bearing metals, the choice depending on whether the alloy is lead-rich or tin-rich. Of the reagents used for lead, the most useful for the present purpose are:

Nos. 4, 5, 6, 8, 11 and 12;

of the reagents for tin,

Nos. 1, 6 and 7

are suitable.

Further reagents are summarized in Table 10.37.

Table 10.37 ETCHING REAGENTS FOR BEARING METALS

No.	*Etchant*	*Remarks*
1	Iodine in potassium iodide solution	Type metals containing small amounts of zinc
2	Iodine, 10% in alcohol	Type metals containing large amounts of zinc
3	Silver nitrate (2–5%) in water	Useful for bearing metals in general

ELECTROLYTIC ETCHING

Bearing metals may be polished electrolytically in a solution containing 60% perchloric acid and acetic anhydride in the ratio of 1 part to 4 parts by volume. If the voltage is reversed after polishing, sensitive etches of most bearing metal materials may obtained.

10.3.27 Cemented carbides and other hard alloys

PREPARATION

Owing to the hardness of these materials, normal methods of preparation cannot be used. In one method, specimens are ground flat on an abrasive wheel, and polished with successively finer grades of diamond powder suspended in olive oil. Polishing should be carried out on a horizontal wheel, the surface of which may be hard-wood, felt or leather. The specimen should be kept cool with running water.

Alternatively, a diamond hone[4] or diamond-impregnated plastic laps may be preferred.[106] The surface of the lap is moulded from 6 g plastic: 1.25 g (6 carats) diamond, giving 0.8 mm thickness over a $7\frac{1}{2}$ cm diameter disc. Two laps are used, with 300 mesh diamond for roughing and with 4–8 μm diamond for intermediate grinding. In use they are lubricated with light paraffin oil. Finishing is by normal diamond polishing on cloth, in two stages.

ETCHING

A number of etching reagents have been developed for these materials, and a selection is given in Table 10.38.

ELECTROLYTIC ETCHING OF TUNGSTEN CARBIDE–COBALT AND TUNGSTEN CARBIDE–TITANIUM CARBIDE–COBALT ALLOYS

Two solutions have been recommended:

1. For tungsten carbide in a matrix of cobalt:

Sodium hydroxide	10%	} in water
Potassium ferricyanide	10%	

On electrolysis at 2 V, the carbide particles are attacked, and the cobalt is almost unaffected.

2. For tungsten and titanium carbides in a matrix of cobalt:

Nitric acid conc.	10 ml
Hydrofluoric acid	10 ml

Titanium carbide is attacked, while tungsten carbide is not attacked.
The cobalt-rich matrix is attacked and dissolved.

Table 10.38 ETCHING REAGENTS FOR CEMENTED CARBIDES, ETC

No	*Etchant*	*Remarks*
1	Potassium hydroxide, 20% in water Potassium ferricyanide, 20% in water Equal volumes are mixed	The cold solution is used as a general reagent
2	Potassium hydroxide 10 g Potassium ferricyanide 10 g Water 10 ml	The boiling solution is used as a general reagent

Table 10.38 ETCHING REAGENTS FOR CEMENTED CARBIDES, ETC.—*continued*

No.	*Etchant*	*Remarks*
3	Aqua regia (20 ml nitric acid + 80 ml hydrochloric acid)	General reagent
4	Hydrofluoric acid 70 ml Nitric acid conc. 30 ml	Rapidly attacks eutectic material in iron–tungsten carbide alloys and iron–molybdenum carbide alloys
5	Picric acid, 2% in alcohol	Develops the eutectic structure in iron–tungsten carbide alloys and iron–molybdenum carbide alloys. The carbides are differentiated
6	Nitric acid, 3% in alcohol	The crystal boundaries in iron–tungsten carbide and iron–molybdenum carbide alloys are developed
7	Mixtures of 5 and 6	Generally effective for this class of material
8	Phosphoric acid 10 ml Hydrogen peroxide 10 ml	Used after successive treatments in Etchants 4 and 1 for molybdenum carbide–titanium carbide–cobalt materials. The titanium carbide with tungsten in solution and the cobalt are darkened; the tungsten carbide with titanium in solution is relatively unaffected[105]
9	Dilute ammonium sulphide	Used after successive treatments in Etchants 4, 1 and 8 for similar materials as recommended for Etchant 8. The carbides are unaffected, but the cobalt-rich matrix is darkened, and differentiated from titanium carbide[105]
10	Potassium permanganate 10 g Potassium hydroxide 5 g Water to 100 ml	WC grey, TiC, pink, TaC gold β phase rapidly attacked

ELECTROLYTIC ETCHING OF IRON–TUNGSTEN–CARBON AND IRON–MOLYBDENUM–CARBON ALLOYS

The use of a 5% solution of potassium ferrocyanide in 5% sodium hydroxide has been suggested. The metallographic effects are very similar to those of Etchant 5 in Table 10.38.

10.3.28 Powdered and sintered metals

PREPARATION

The preparation of powders, pressed compacts, and sintered metals is a specialized process, and requires special methods.

For the examination of powders, a suitable mounting may be made in plastic. The medium chosen will depend on many factors such as the melting point, reactivity and hardness of the metal of which the powder is composed. The plastic mounting may be made simply by mixing the metal powder with an appropriate amount of the mounting medium, and heating and pressing the composite sample in the usual way. Grinding, polishing and etching are then carried out as for the metal involved.

In pressed compacts and sintered materials, voids are present; these tend to pick up grinding and polishing materials, and to absorb etching reagents, so that difficulty may be experienced at all stages of the preparation. Comparatively little work has been carried out to determine precisely the best technique for the metallographic preparation of such specimens but impregnation with plastic is sometimes helpful (*see* section 10.2—*Microscopic examination, mounting*, p. 10–6).

10.4 Electron metallography

The application of electron microscopy to the study of the microstructure of metals and alloys is termed 'electron metallography'. There are basically two types of electron microscope: one operating primarily as a transmission instrument and the other known as a scanning electron microscope which operates in the reflection or emission modes. Combined scanning/transmission

electron microscopes (STEM) are increasing in popularity. Details of the latest developments in this field can be found in reference 150.

10.4.1 Transmission electron microscopy

As electrons are readily scattered by metals, the materials and components used industrially cannot in general be examined directly in the transmission microscope, so that special preparation techniques are required.[107–113] In *the replica technique* the surface topography of the metal is reproduced in a thin film of a substance which is not decomposed by the action of the electron beam, usually carbon. Generally, the technique involves polishing and etching a section through the metal, as in optical metallography, when the structure so developed can be reproduced either using a two-stage plastic/carbon or a single-stage direct carbon replica. In the former case the plastic most often used is cellulose triacetate sheets of which 20–250 μm thick are softened in acetone, laid on to the prepared metal surface and as the acetone evaporates the plastic hardens and contracts into the surface features. It is then carefully removed from the metal, and a layer of carbon 200–300 Å thick, is evaporated *in vacuo* on to the replica face, after which the plastic is dissolved in acetone leaving a secondary carbon replica. The more direct technique is to evaporate the carbon layer directly on to the prepared metal surface. Then because the carbon layer is somewhat porous it may be removed by re-etching the surface to dissolve the metal away from the carbon film. A particularly useful variation of this technique is the carbon extraction replica, which is used for the examination of multiphase alloys. The etching of the specimen, both prior to and after deposition of the carbon film, is controlled so that one phase, usually the matrix, is dissolved at a much faster rate than the other phase(s). In this way the second phase precipitate particles present in most alloys, except those of aluminium, can be extracted from the matrix on to the carbon replica film and because these particles are attached to the carbon, their distribution in the replica is normally identical to that in the original bulk metal sample. Prior to the examination in the microscope the pieces of carbon replica are collected on to fine mesh support grids, usually made of copper. The resolution attainable in carbon replicas is typically 20 Å and they may be usefully examined at all magnifications up to about 40 000 times. The carbon extraction replica technique is the most popular replication procedure used in the examination of all types of steels, copper alloys, nickel and cobalt-based superalloys, titanium alloys and uranium alloys. Details of replica techniques suitable for each of these types of alloy are given in Table 10.39. In addition to the replication of metallographically prepared surfaces, replica transmission microscopy is also used to study the fracture surfaces of failed metallic components, a technique known as electron fractography. The procedure is basically as described above, except that the specimen is not prepared in any way except possibly careful cleaning to remove corrosion products, the plastic or carbon being deposited directly on to the fracture surface. The contrast in such replicas may be enhanced by shadowing the surface of the carbon with a heavy metal such as gold or palladium.

Table 10.39 EXTRACTION REPLICA TECHNIQUES FOR INDUSTRIAL ALLOYS

Alloy	*Technique*	*Reference*
Copper alloys such as aluminium bronze, aluminium silicon bronze and cupro-nickels	(a) Etch in ferric chloride and hydrochloric acid in water for approx. 30 s (b) Deposit carbon (c) Re-etch in the acid ferric chloride solution for 2–5 min, wash in alcohol, float off replicas in distilled water	109
	(a) Etch in saturated aqueous solution of sodium bisulphate for approx. 2 min (b) Deposit carbon (c) Re-etch for several minutes in sodium bisulphate solution, back with layer of Bex† film to dry strip. Dissolve Bex in acetone	109
	(a) Etch in alcoholic ferric chloride (b) Deposit carbon (c) Re-etch in either Disapol* D2 electrolyte at 5 V or E5 electrolyte at 30 V	128

* Disapol is a trade name of H. Struers Chemiske Laborotorium, Skindergade 38, Copenhagen.
† Bex is a proprietary brand of cellulose triacetate obtainable from Polaron Equipment Ltd., Watford, England.

Table 10.39 EXTRACTION REPLICA TECHNIQUES FOR INDUSTRIAL ALLOYS—*continued*

Alloy	*Technique*	*Reference*
Mild and low alloy steels	(a) Etch in ethyl alcohol + 2/5% nitric acid for 10–40 s (b) Deposit carbon (c) Strip by etching as in (a)	129
	(a) Etch in 5 g cupric chloride, 40 ml hydrochloric acid, 30 ml water, 25 ml ethyl alcohol (b) Deposit carbon (c) Strip by etching as in (a) also electropolish in ethyl alcohol + 10% nitric acid at 10 V Also use above techniques, without step (a), for fracture surfaces	129
High chromium and alloy steels	(a) Etch in methyl alcohol + 10% hydrochloric acid (b) Deposit carbon (c) Strip by etching as in (a)	130
High speed steels	(a) Electropolish in solution containing 50 ml perchloric acid (s.g. 1.54), 950 ml glacial acetic acid, stainless steel cathode, 1 A cm^{-2} with applied voltage of 64 V (b) Etch in Vilella's reagent (c) Deposit carbon (d) Strip by etching in solution of 5% nitric acid in alcohol containing few drops of hydrofluoric acid (etching time ~ 1.5 min)	131
Stainless steels	(a) Electropolish in 5% perchloric acid, 95% glacial acetic acid + 10 g l^{-1} nickel chloride + 20 g l^{-1} chromic anhydride at 45 to 60 V (b) Etch in 20% hydrochloric acid + 80% of 10% aqueous solution of chromic anhydride at 6.5 V for approx. 5 s (c) Deposit carbon (d) Strip by etching in aqueous solution containing 50% hydrochloric acid for several hours	109
Nickel alloys	For extraction of carbides (a) Mechanical polish to ¼ μm diamond, electropolish in 10% perchloric acid + 90% acetic acid at 40 V (b) Etch 15 s in 25 g ferric chloride, 25 g cuprous chloride, 100 ml nitric acid, 300 ml hydrochloric acid (c) Deposit carbon (d) Re-etch for 30 s as in (b) (e) Strip carbon by electropolishing at 40 V in 20% perchloric acid in ethyl alcohol	109
	For extraction of γ' particles (a) Polish as in (a) above (b) Etch in 10% phosphoric acid in water at 30 V for 1 s (c) Deposit carbon (d) Strip carbon by electropolishing at 40 V in 20% perchloric acid in ethyl alcohol	109
Titanium alloys	For α alloys (a) Electropolish in methyl alcohol, butyl cellosolve, perchloric acid solution (b) Etch in 2% hydrofluoric acid in saturated aqueous solution of oxalic acid (c) Strip replicas in 1 part hydrofluoric acid, 1 part nitric acid, 30 parts water	132
	For $\alpha + \beta$ alloys (a) Electropolish as (a) above (b) Etch in aqueous solution 1% hydrofluoric acid, 2% nitric acid (c) Strip replicas as (c) above	133

Table 10.39 EXTRACTION REPLICA TECHNIQUES FOR INDUSTRIAL ALLOYS—*continued*

Alloy	*Technique*	*Reference*
Titanium alloys (*cont.*)	(a) Etch for 5 s in aqueous solution containing 1% hydrofluoric acid, 2% nitric acid (b) Deposit carbon (c) Strip by scoring carbon into squares and etching for 20 s in 1 part hydrofluoric acid, 1 part nitric acid, 30 parts water	109
Uranium alloys	(a) Mechanical polish down to $\frac{1}{4}$ µm diamond (b) Polish-attack for 20 min on terylene cloth using 50 g l^{-1} of chromic anhydride, 100 ml glacial acetic acid, 100 ml water + γ alumina (c) Electrolytic etch, 2% citric acid, 0.5% nitric acid, 97.5% water at 6 V for approx. 40 s (d) Deposit carbon (e) Score carbon film into squares, electropolish in bath given in (c) at 15 V for 10–20 min. Float off in water	109
	(a) Mechanical grind to 6 (b) Electropolish in 50 ml phosphoric acid, 50 ml water. Open circuit of 30 V, c.d. of 4.65 kA m^{-2} for 40 s (c) De-oxidize in 75% sulphuric acid, 18% glycerol, 7% water at 10 V, initial current density is 2.32 kA m^{-2} falls to 0.7 A on completion of deoxidation (d) Etch in solution of 2% chromic anhydride in 25% acetic acid at 2 V (c.d. 75 A m^{-2}) for approx. 20 s with platinum cathode (e) Deposit carbon (f) Strip by etching as in (d) for 10 to 20 s. If unsuccessful, electropolish for few seconds as in (b)	109

The second type of specimen preparation procedure, *the thin foil technique* involves reducing the thickness of the metal until it can be penetrated by the electron beam of the microscope. The limiting thickness depends on the atomic number of the metal and the electron accelerating voltage at which the microscope is operated. Thus for conventional instruments operating at 100 kV the thickness decreases from about 2000 Å for aluminium to about 300 Å for uranium, whereas using a high voltage microscope at 1000 kV an aluminium specimen of up to about 9 µm can be penetrated. The usual method for reducing the thickness of the specimen is by electropolishing[114–119] and a widely used procedure requires that the starting specimen is in the form of a disc up to 3 mm diameter and 0.5 mm thick, which can be readily prepared from the bulk material by processes such as grinding or machining.[120–125] These discs are then electropolished until a small hole(s) is formed near the centre, when it is usually found that the metal adjacent to the edge of the hole is sufficiently thin to transmit electrons. Using these disc techniques thin foils can easily be produced from selected areas or from a required distance with respect to a reference surface. Electron microscopes and associated techniques are now capable of resolutions of 3–5 Å. Line imaging using phase contrast enables lattice planes to be resolved. High resolution can only be attained in thin foils of ferromagnetic materials such as ferritic steels, by ensuring that the bulk of specimen is as small as possible with the perforation occurring in the centre of the sample, to minimize the effects of the foil on the magnetic field of the objective lens. Modification of the structure of a metal may occur during the preparation of thin foils or during subsequent examination in the microscope. Thus defect structures may be altered because of the relaxation of long range stresses during thinning or due to mechanical damage of the thin foil by careless handling. Also metastable alloys may undergo a phase transformation when in thin foil form, either because the surface acts as a preferential nucleating site for nucleation and growth transformations, or because in materials which undergo a phase transformation by shear, the large stresses produced by the transformation may be relaxed at the surface of the foil. The thin foil technique has been used for studying in detail the microstructure of all the common industrial alloys, and some suitable preparation procedures are given in Table 10.40.

Table 10.40 THIN FOIL TECHNIQUES FOR INDUSTRIAL ALLOYS[107]

Material	*Technique*	*Solution*	*Conditions*
Ag–Zn	Jet	9% KCN, 91% H_2O	
Al	Window	1 part nitric acid, 3 parts methanol	−70 °C, 40 V
Al–Cu	Chemical	94 parts phosphoric acid, 6 parts nitric acid	
Al–Au alloys	Window	20% perchloric acid, 80% methanol	16–18 V, 100 cm^{-2}, −55 to −65 °C
Au	Window (3 mm discs)	100 ml CH_3COOH, 20 ml HCl, 3 ml H_2O	Stainless steel cathode, 32 V, 15 °C
	Electrolytic	(a) 15% glycerol, 35% 50% HCl (b) 133 ml glacial CH_3COOH, 25 g CrO_3, 7 ml H_2O	30 V, −30 °C, 1.5 A cm^{-2}— fast polish Finish after (a) at 22 V, 0.8 A cm^{-2}, 0 °C
Be, Be–Cu	Window	20% perchloric acid, 80% ethanol	−30 °C, 40 V
Co–Fe	(a) Chemical	50% phosphoric acid, 50% hydrogen peroxide	
	(b) Jet	20% perchloric acid, 80% methanol	−20 °C
Cu–Ni–Fe alloys	Chemical	20 ml acetic acid, 10 ml nitric acid, 4 ml HCl	
Cu–Ti	Jet	750 ml acetic acid, 300 ml phosphoric acid, 150 g chromic acid, 30 ml distilled H_2O	30–40 V, 45–55 A
Fe–Al–C	Chemical	HF, H_2O, H_2O_2 (1 : 3 : 16)	
Fe_3Si	Window	1% perchloric acid, 2.5% hydrofluoric acid in methanol	−77 °C
Gd–Ce alloys	Window	1% perchloric acid, 99% methyl alcohol	−77 °C
Hf	(a) Jet	45 parts nitric acid, 45 parts H_2O, 8 parts HF	
	(b) Jet	2 parts perchloric acid, 98 parts ethanol	40–45 V, 16–20 mA, −77 °C
In	Window: from 0.1 mm thick	33% HNO_3, 67% methanol	−40 °C
Mg		(a) 20% $HClO_4$, 80% ethanol (b) 375 ml H_3PO_4, 625 ml ethanol	Fast polish, 0 °C Finish at 15 V, 0 °C, lowest current
	Chemical	6% nitric acid, 94% H_2O	3 °C
Mo	Jet	1 part sulphuric acid, 7 parts methanol	10 V
Nb	Chemical	60% HNO_3, 40% HF	0 °C
Nb alloys	Window	100 ml lactic acid, 100 ml sulphuric acid, 20 ml HF	40 °C, ~0.4 A cm^{-2}
Ni steels Stainless steels	Chemical	50 ml 60% H_2O_2, 50 ml H_2O, 7 ml HF	Place specimen in H_2O_2 solution, then add HF until reaction starts; produces 1000 Å foils which can then be finished by electro-polishing by standard chromic-acetic electropolishing (courtesy Republic Steel Corp.)
Ni alloys Cu–Ni–Fe	Jet	1 part HNO_3, 3 parts CH_3OH	6–10 V, 18–30 mA, −30 °C

Table 10.40 THIN FOIL TECHNIQUES FOR INDUSTRIAL ALLOYS[107]—*continued*

Material	*Technique*	*Solution*	*Conditions*
Ni	Jet	20% perchloric acid in ethanol	
Ni–Al alloys	Jet	20% sulphuric acid, 80% methanol	Dished at 150 V, final polish in same solution at 10–12 V
Ni and Ni–Fe	Jet	8 parts 50% sulphuric acid, 3 parts glycerine	Less than 10 °C, 1.3 A cm^{-2}
Rene 95	Jet	250 ml methanol, 12 ml perchloric acid, 150 ml butylcellusolve	−35 °C, 65 V
Th	Window	5% perchloric acid, 95% methanol	−77 °C, 3–10 V
Pt	Electrolytic	H_2SO_4 (96%), HNO_3 (65%), H_3PO_4 (80%)	0.2–0.5 A cm^{-2}, 20–30 °C
Re	Window	Ethyl alcohol, perchloric acid, butoxyethanol (6 : 3 : 1)	−40 °C, 35 V
Ta	Chemical	3 parts HNO_3, 1 part HF	−10 °C, immerse in Petri dish after lacquering
Ta	Jet	1 part sulphuric acid, 5 parts methanol	−5 °C, current density of 0.5 A cm^{-2}
Ti	Jet	1 part HF, 9 parts sulphuric acid	
Ti–Nb	Chemical	4 parts nitric acid, 1 part HF	
TiC	Jet	6 parts nitric acid, 2 parts HF, 3 parts acetic acid	100 V
Ti and Ti alloys	Jet	30 ml $HClO_4$, 175 ml *n*-butanol, 300 ml CH_3OH	15 V, 0.1 A cm^{-2}, may need ion thinning at end to remove contamination layer
U	Jet	1 part perchloric acid, 10 parts methanol, 6 parts butylcellusolve	−20 °C, 35–45 V
UO_2 (sintered)	Chemical	10 ml HOAc, 20 ml sat. CrO_3, 5 ml 40% HF, 7 ml HNO_3 ($d = 1.42$)	
	or Chemical	20 ml H_3PO_4 ($d = 1.75$), 10 ml HOAc, 2 ml HNO_3 ($d = 1.42$)	
V	Chemical	2 parts HF, 1 part nitric acid	Less than 10 °C
V	Jet	20% sulphuric acid in methanol	
Zn–Al	Chemical	50–70% nitric acid in water	
Zn–Al	Window	90% methanol, 10% perchloric acid	
Zr–25% Ti	Chemical	50 ml nitric acid, 40 ml H_2O, 10 ml HF	
Zr alloys	Jet	5% perchloric acid, 90% ethanol	70 V, below −50 °C

Selected area electron diffraction analysis is extensively used for the identification of second phase particles in carbon extraction replicas and thin foils, and individual particles down to ~ 1000 Å diameter can be analysed. Electron diffraction effects can also be obtained from other microstructural features such as GP zones in age-hardening alloys, order–disorder transformations and stacking faults, so that the interpretation of diffraction patterns can be difficult and requires extreme care.[107, 108, 112, 126, 127] Diffraction patterns from extraction replicas are normally

calibrated (to determine the camera constant) by evaporating a substance whose interplanar spacings are known accurately, such as gold or thallium chloride, on to the carbon film. In the case of second phase particles in thin foils, the diffraction patterns are usually calibrated using the matrix phase. Spot patterns are obtained from single crystal particles and the patterns are effectively an enlarged image of a plane of the reciprocal lattice of the crystal. If a large number of small particles are contributing to the diffraction pattern, a ring pattern is obtained. In either case the interplanar spacings can be calculated from the equation: $d=(L\lambda)/r$, where L is the camera length, λ the wave-length of the electrons, and r is half the distance separating corresponding spots in the single crystal spot pattern, or the radius of the diffraction ring in a polycrystalline ring pattern. L is usually obtained from the calibration pattern. By calculating the d values for 3 or 4 sets of diffraction spots or rings and determining the symmetry of the diffraction pattern, it is possible to index the spots or rings in terms of their Miller indices and therefore to determine the crystal structures and parameters of the diffracting phase. The best accuracy possible with selected area electron diffraction is about 0.1% but is more commonly in the range 0.5–1.0%.

However, to identify unambiguously the structure of a single particle it is often necessary to tilt the diffracting crystal into two or three prominent diffracting zones. Also, as the contrast in images of thin foils arises mainly from Bragg diffraction of the electrons, the contrast from fine second phase particles and defect structures depends critically upon the orientation of the foil with respect to the electron beam. Therefore modern instruments incorporate special stages which allow the specimen to be tilted and rotated. It is also useful to have a facility for cooling the specimen, to reduce the amount of contamination which can occur if one area of the foil is examined for a prolonged period. Stages designed to enable the specimen to be heated or strained are of only limited value in electron metallography, because due to the high surface area: volume ratio, the rate and morphology of structural changes which occur during heating or straining of thin foils are usually different from those occurring in bulk material.

Modern microscopes now have fitted to them detectors to collect the X-rays generated by the interaction between the electron beam and the metallic foil specimen. The wavelengths of X-rays are then separated by either dispersive or non-dispersive systems and from this a semiquantitative analysis of the elements present can be obtained, usually from a volume of about 1–2 μm. The electron microscope for microanalysis (EMMA) has been developed to make more accurate analyses from areas of $<0.5\,\mu m$.

A summary of recent developments in surface imaging in the TEM can be found in reference 148.

10.4.2 Scanning electron microscopy

The use of scanning electron microscopy to study the surface structure of metals has increased tremendously over the last few years (for example, *see* refs. 143–145). This has been due to a number of advantages which this form of microscopy enjoys compared to optical or transmission electron microscopy, namely:

1. The depth of focus in the image is very large, at least 300 times that of a conventional optical microscope, and the resolution is typically better than 100 Å.
2. Compared to transmission electron microscopy the preparation required to produce a sample for examination by scanning microscopy is extremely simple. Normally all that is required is to mount a specimen, typically 3 cm dia. and 0.5 cm high, on to an aluminium stub using a conducting adhesive. If the sample contains non-conducting material on the surface, which will tend to charge-up during examination, it is also necessary to deposit a thin conducting film, usually of carbon or a gold/palladium alloy, by evaporation in a vacuum.
3. Images obtained by a scanning microscope are generally much easier to interpret than those from a transmission microscope, so that it is often possible to obtain the desired result from an examination of the image as it is formed on the viewing screen.

In the scanning microscope a beam of electrons with energies in the range 1–30 kV is focused to a spot ~100 Å in diameter and made to scan the surface to be examined in a rectangular raster. Primary electrons are reflected and secondary electrons emitted from the surface and are focused with an electrostatic electrode on to a biased scintillator. The light produced is transmitted via a perspex light pipe to a photomultiplier and the signal generated is used to modulate the brightness of an oscilloscope spot which traverses a raster in exact synchronism with the electron beam at the specimen surface. The magnification of the projected image is easily adjusted, because it is simply the ratio of the rasters of the electron beam and oscilloscope. In modern scanning microscopes the X-rays emitted from the specimen surface under the action of the primary electron beam can also

be analysed to yield information on the chemical composition. Each element in the specimen surface emits X-rays of characteristic wavelengths and energies. The wavelengths may be separated by a dispersive technique using a spectrometer and different energy levels may be distinguished with high resolution X-ray detectors, such as the lithium drifted silicon semiconductor radiation detector. This latter technique is particularly suitable for use in conjunction with scanning microscopes, in which the requirements of image resolution necessitate the use of lower electron beam intensities than in purpose-built X-ray microprobes.

10.4.3 Electron spectroscopy

This is a technique for studying the energy distribution of electrons ejected from a material on irradiation by a source of ionizing radiation such as X-rays, ultra-violet light or electrons.

When X-ray radiation is used as the ionizing source, the technique is called X-ray photoelectron spectroscopy (XPS) or electron spectroscopy for chemical analysis (ESCA). If ultra-violet light is used, the technique is called ultra-violet photoelectron spectroscopy (UPS).

Both electron and high-energy X-ray beams can also cause a secondary electron to be emitted from the atoms and the analysis of the energy of these electrons (Auger electrons) is known as Auger spectroscopy (AES).

The analysis of XPS and Auger spectroscopy has now been developed to an extent that not only can the atomic species be identified, but also information can be obtained about its binding energy, charge and valency. As the photoelectrons and Auger electrons can only escape from a region of 3–50 Å below the surface, the region analysed is truly only the surface and not more than a few atomic spacings below the surface. Not only can the individual elements be clearly resolved, but it is also possible to detect accurately changes in binding energy when the element exists in forms with different valencies.

The latest instruments combine scanning electron microscopy and energy dispersive analysis of X-rays with scanning Auger spectroscopy, so that it is possible to compare electron images with Auger images for specific elements. An analysis of X-rays generated from a depth of 0.5 μm can be contrasted with a simultaneous analysis of Auger electrons from the same area, but from a depth of 3–50 Å.[147] The low energy diffracted electrons can be collected and used as an electron diffraction pattern to provide structural information about the surface (LEED—low energy electron diffraction) or passed through an imaging column to form an image of the surface in bright or dark field (LEEM—low energy electron microscopy).[149]

10.5 Quantitative image analysis

Image analysis may be defined as the science of making geometric and densitometric measurements and classifications of selected features in images formed by optical, transmission electron and scanning electron microscopes and from photographs, X-rays and radiographs. A number of image analysing computers are available which allow fast, accurate measurements and classifications, so that tasks in R & D, quality control and routine assessment which previously were impossible are now both possible and economic. The term 'quantitative image analysis' is virtually synonymous with Quantimet, a trade name of Image Analysis Computers Ltd., Cambridge, England. In modern image analysing computers the image is scanned by a vidicon or plumbicon scanner, whose output is passed to a detector. This either selects features for measurement in terms of their common grey level characteristics or alternatively the scanner output can be passed to a densitometer, which will assess the optical density at each point in a feature and compute its integrated density. The signal from the detector can be amended to allow for imperfect feature definition or can be passed directly to one or more of several alternative modules which make the required measurements. Alternatively, or additionally, results can be passed to data output systems, such as a desk-top calculator, or to a supervisor module, which screen large numbers of fields of view and select only those with interesting features. The entire operation can be automatically controlled by a simple programmer or it can be manually controlled by switches.

A large number of types of measurements can be made using an image analysing computer including (1) number, (2) area, (3) length, (4) perimeter, (5) mean linear intercept, (6) form factor, (7) optical density, (8) size distribution, (9) pattern or shape recognition. Typical uses include quality control of inclusions in steels, fibre classification, size distribution of powders, phase concentrations and grain morphology and pore sizing in composites.

10.6 Scanning acoustic microscopy

Scanning acoustic microscopy is a non-destructive analytical technique which uses the information from an ultrasonic probe which is scanned over the surface of the test sample to create a complete picture of the shapes, sizes and exact positions of defects, inclusions and other metallographic features which are displayed as full (false) colour screen or printed images.

The ultrasonic probe is used in pulse-echo mode as a B- or C-scan. The amplitude and phase of the reflected signal depend on the magnitude and the rate of change in acoustic impedance as it is reflected at an interface or other feature.

By time gating the returning acoustic wave train and detecting any change in phase, the variations can be encoded and analysed digitally to convert them into shades of colour or density to build up a two-dimensional image of the sample.

The scanning acoustic microscope comprises a scanning frame which carries an orthogonal *XYZ* probe transport system. Motion of the probe in the three axes is provided by three independent stepper motors. The system incorporates a pulser–receiver circuit which is driven by a computer with appropriate software.

The sample to be scanned is placed in a tank containing a liquid capable of transmitting acoustic waves from the probe into the sample. The liquid is usually water but it can be a suitable organic liquid. The motors then move the probe over the sample in a raster pattern. The computer can be programmed to follow curved as well as planar surfaces or interfaces.

Scanning acoustic microscopy is suitable for imaging defects and inclusions in ceramic and composite as well as metallic materials. It is also useful for studying soldered and diffusion-bonded interfaces and for any internal artefact whether deliberately introduced or not.

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11 Equilibrium diagrams

11.1 Index of binary diagrams

For numbers in parenthesis see 11.3 Acknowledgements.

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Cr–Pt 11–217 (8)
Cr–Pu 11–218
Cr–Re 11–218
Cr–Rh 11–218 (8)
Cr–Ru 11–219
Cr–S 11–219
Cr–Sc 11–219 (8)
Cr–Si 11–220
Cr–Sn 11–220
Cr–Ta 11–221
Cr–Tb 11–221 (8)
Cr–Ti 11–221 (8)
Cr–U 11–222 (8)
Cr–V 11–222
Cr–W 11–223 (1)
Cr–Y 11–223
Cr–Zn 11–223
Cr–Zr 11–224 (1)

Cs–Ga 11–224 (8)
Cs–Hg 11–225
Cs–In 11–225 (3)
Cs–K 11–226
Cs–Na 11–226
Cs–Rb 11–226
Cs–S 11–226
Cs–Sb 11–227
Cs–Te 11–227 (8)
Cs–Tl 11–227 (8)

Cu–Er 11–228 (8)
Cu–Eu 11–228 (3)
Cu–Fe 11–229 (8)
Cu–Ga 11–229 (8)
Cu–Gd 11–230 (3)
Cu–Ge 11–230 (8)
Cu–Hf 11–231 (4)
Cu–Hg 11–231
Cu–In 11–232 (8)
Cu–Ir 11–232 (8)
Cu–La 11–233 (1)
Cu–Li 11–233
Cu–Mg 11–234
Cu–Mn 11–234 (8)

Cu–Nd 11–235 (3)
Cu–Ni 11–236
Cu–O 11–235 (8)
Cu–P 11–235
Cu–Pb 11–236 (1)
Cu–Pd 11–237 (8)
Cu–Pr 11–237
Cu–Pt 11–238
Cu–Pu 11–238
Cu–Rh 11–239 (8)
Cu–S 11–239 (8)
Cu–Sb 11–240 (8)
Cu–Se 11–240
Cu–Si 11–241 (8)
Cu–Sm 11–241 (8)
Cu–Sn 11–242 (8)
Cu–Sr 11–242 (8)
Cu–Te 11–243
Cu–Th 11–243 (8)
Cu–Ti 11–244 (4)
Cu–Tl 11–244
Cu–U 11–245 (8)
Cu–V 11–245
Cu–Y 11–245 (8)
Cu–Yb 11–246 (8)
Cu–Zn 11–246 (8)
Cu–Zr 11–247 (8)

Dy–Er 11–247 (8)
Dy–Fe 11–248
Dy–Ga 11–248 (2)
Dy–Ge 11–249 (8)
Dy–Ho 11–249 (8)
Dy–In 11–250 (8)
Dy–Mn 11–250 (8)
Dy–Ni 11–251 (8)
Dy–Sb 11–251 (8)
Dy–Zr 11–252

Er–Fe 11–252 (8)
Er–Ho 11–252 (8)
Er–In 11–253 (3)
Er–Ni 11–253 (8)
Er–Rh 11–254 (8)
Er–Tb 11–254 (8)
Er–Ti 11–254
Er–V 11–254
Er–Y 11–255 (8)
Er–Zr 11–255

Eu–In 11–256 (8)

Fe–Ga 11–256 (8)
Fe–Gd 11–257 (8)
Fe–Ge 11–257
Fe–Hf 11–258
Fe–Ho 11–258 (8)
Fe–In 11–259 (8)
Fe–Ir 11–259
Fe–La 11–260
Fe–Mg 11–260 (8)
Fe–Mn 11–261 (8)
Fe–Mo 11–262 (8)
Fe–N 11–262 (8)
Fe–Nb 11–263
Fe–Ni 11–264
Fe–O 11–264
Fe–Os 11–264
Fe–P 11–265
Fe–Pb 11–266
Fe–Pd 11–266 (8)
Fe–Pt 11–267 (8)
Fe–Pu 11–267 (8)
Fe–Re 11–268 (8)
Fe–Ru 11–268 (8)
Fe–S 11–269 (8)
Fe–Sb 11–270
Fe–Sc 11–270 (8)
Fe–Se 11–271 (8)
Fe–Si 11–271 (8)
Fe–Sm 11–272 (8)
Fe–Sn 11–272 (8)
Fe–Ta 11–273 (8)
Fe–Ti 11–273
Fe–U 11–274 (8)
Fe–V 11–274 (8)
Fe–W 11–275
Fe–Y 11–275 (8)
Fe–Zn 11–276 (8)
Fe–Zr 11–276

Ga–Gd 11–277 (2)
Ga–Ge 11–277 (8)
Ga–Hg 11–277 (8)
Ga–In 11–278 (8)
Ga–K 11–278
Ga–La 11–278 (2)
Ga–Li 11–279 (8)
Ga–Mg 11–299 (8)
Ga–Mn 11–280 (8)
Ga–Na 11–280
Ga–Nb 11–281 (8)
Ga–Nd 11–281 (2)
Ga–Ni 11–282 (8)
Ga–P 11–282
Ga–Pb 11–283
Ga–Pd 11–283 (8)
Ga–Pr 11–283
Ga–Pu 11–284
Ga–Rb 11–285 (8)
Ga–Sb 11–284 (8)
Ga–Se 11–285 (2)
Ga–Si 11–286
Ga–Sm 11–286 (2)
Ga–Sn 11–286
Ga–Te 11–286
Ga–Tl 11–287
Ga–Tm 11–287 (3)
Ga–U 11–288 (8)
Ga–V 11–288 (8)
Ga–Y 11–289 (2)
Ga–Yb 11–289 (8)
Ga–Zn 11–290 (1)

Gd–Ge 11–290 (8)
Gd–In 11–291 (3)
Gd–La 11–291 (1)
Gd–Mg11–292
Gd–Mn 11–292
Gd–Ni 11–293 (8)
Gd–Pb 11–293 (8)
Gd–Pd 11–294 (3)
Gd–Rh 11–294 (8)
Gd–Ru 11–295 (8)
Gd–Sc 11–295 (8)
Gd–Ti 11–295
Gd–Y 11–296
Gd–Zr 11–296

Ge–Hf 11–297
Ge–In 11–297
Ge–Mg 11–297 (8)
Ge–K 11–298 (8)
Ge–Mn 11–298 (8)
Ge–Mo 11–299 (8)
Ge–Ni 11–299 (3)
Ge–Pb 11–300
Ge–Pd 11–300 (8)
Ge–Pt 11–301 (8)
Ge–Rb 11–301 (8)
Ge–Rh 11–301 (8)
Ge–Ru 11–302 (8)
Ge–S 11–302
Ge–Sb 11–302
Ge–Se 11–302
Ge–Si 11–303
Ge–Sn 11–303 (8)
Ge–Sr 11–304 (8)
Ge–Te 11–304
Ge–Ti 11–304 (8)
Ge–U 11–305
Ge–Y 11–306 (8)
Ge–Zn 11–306 (8)
Ge–Zr 11–306 (8)

H–Nb 11–307
H–Sr 11–307 (8)
H–Ti 11–308 (8)
H–Zr 11–308 (8)

Hf–Ir 11–309 (8)
Hf–Mn 11–309 (8)
Hf–Mo 11–310 (8)
Hf–Nb 11–310
Hf–Ni 11–311 (8)
Hf–O 11–311 (8)
Hf–Re 11–311
Hf–Sn 11–312
Hf–Ta 11–312 (8)
Hf–Th 11–313
Hf–Ti 11–313
Hf–U 11–314 (8)
Hf–W 11–314 (8)
Hf–Zr 11–314 (1)

Hg–In 11–315
Hg–K 11–315
Hg–Li 11–315
Hg–Mg 11–316
Hg–Mn 11–316 (8)
Hg–Na 11–317
Hg–Pb 11–317
Hg–Rb 11–317
Hg–Rh 11–317 (8)
Hg–Sb 11–318 (8)
Hg–Sn 11–318 (8)
Hg–Te 11–318
Hg–Tl 11–319

Hg–U 11–319 (8)
Hg–Zn 11–319

Ho–Tb 11–319 (8)

In–K 11–320 (8)
In–La 11–320 (3)
In–Li 11–321 (8)
In–Mg 11–321 (8)
In–Mn 11–321 (8)
In–Na 11–322 (8)
In–Nd 11–322 (3)
In–Ni 11–323 (8)
In–Pb 11–323 (8)
In–Pd 11–324
In–Pr 11–325
In–Sb 11–326
In–Se 11–326
In–Si 11–327 (8)
In–Sn 11–327 (8)
In–Sr 11–328 (8)
In–Te 11–328
In–Ti 11–329
In–Tl 11–329
In–Y 11–330 (3)
In–Yb 11–330
In–Zn 11–330 (8)
In–Zr 11–330 (8)

Ir–Mn 11–331 (8)
Ir–Mo 11–331
Ir–Nb 11–331
Ir–Os 11–332
Ir–Pd 11–332
Ir–Pt 11–333
Ir–Re 11–333
Ir–Th 11–334
Ir–Ti 11–334 (8)
Ir–W 11–335

K–Li 11–335
K–Mg 11–335
K–Na 11–336
K–Pb 11–336
K–Rb 11–336
K–S 11–336
K–Sb 11–337
K–Se 11–337
K–Sn 11–338
K–Tl 11–338
K–Zn 11–338

La–Mg 11–339 (8)
La–Mn 11–339 (8)
La–Nd 11–340
La–Ni 11–340 (8)
La–Pb 11–340
La–Rh 11–341 (8)
La–Sb 11–341
La–Sn 11–342 (8)
La–Tl 11–342 (8)
La–V 11–343
La–Y 11–343 (1)

Li–Mg 11–344 (8)
Li–Mn 11–344
Li–Na 11–344
Li–Pb 11–344 (8)
Li–Pd 11–345
Li–S 11–345
Li–Si 11–346
Li–Sn 11–346
Li–Sr 11–347
Li–Tl 11–348
Li–Zn 11–349

Mg–Mn 11–350 (8)
Mg–Na 11–350
Mg–Ni 11–351
Mg–Pb 11–351
Mg–Pr 11–351 (8)
Mg–Pu 11–352
Mg–Sb 11–352
Mg–Sc 11–353 (8)
Mg–Si 11–353
Mg–Sn 11–354 (8)
Mg–Sr 11–354 (1)
Mg–Th 11–355
Mg–Ti 11–355
Mg–Tl 11–355
Mg–U 11–356 (8)
Mg–Y 11–356 (8)
Mg–Zn 11–357 (8)
Mg–Zr 11–357 (8)

Mn–N 11–358 (8)
Mn–Nb 11–359 (8)
Mn–Nd 11–359 (8)
Mn–Ni 11–360 (8)
Mn–O 11–360 (8)
Mn–P 11–361 (6)
Mn–Pb 11–361 (6)
Mn–Pd 11–361 (8)
Mn–Pt 11–362 (8)
Mn–Pu 11–362
Mn–Rh 11–362 (6)
Mn–Ru 11–363 (8)
Mn–S 11–364 (8)
Mn–Sb 11–364
Mn–Si 11–365 (8)
Mn–Sm 11–365 (8)
Mn–Sn 11–366 (8)
Mn–Tb 11–366 (8)
Mn–Ti 11–367
Mn–Tl 11–368
Mn–U 11–368 (8)
Mn–V 11–368 (8)
Mn–Y 11–369 (8)
Mn–Zn 11–370, 371 (8)
Mn–Zr 11–372

Mo–Nb 11–373 (4)
Mo–Ni 11–373 (8)
Mo–Os 11–373 (8)
Mo–Pd 11–374 (4)
Mo–Pt 11–374 (3)
Mo–Re 11–375 (8)
Mo–Rh 11–375
Mo–Ru 11–375 (8)
Mo–S 11–376 (4)
Mo–Si 11–376 (4)
Mo–Ta 11–377
Mo–Th 11–377 (4)
Mo–Ti 11–378 (1)
Mo–U 11–378 (8)
Mo–V 11–379
Mo–W 11–379 (8)
Mo–Y 11–379
Mo–Zr 11–380 (8)

N–Ti 11–380 (8)

Na–Pb 11–381
Na–Rb 11–381
Na–S 11–381
Na–Sb 11–382
Na–Se 11–382
Na–Sn 11–383 (8)
Na–Sr 11–384 (1)
Na–Te 11–384
Na–Th 11–385 (8)
Na–Tl 11–385
Na–Zn 11–385 (1)

Nb–Ni 11–386
Nb–O 11–387
Nb–Os 11–387 (2)
Nb–Re 11–388 (8)
Nb–Rh 11–388
Nb–Ru 11–389 (4)
Nb–Sc 11–389 (2)
Nb–Si 11–390 (8)
Nb–Sn 11–390 (8)
Nb–Ta 11–391
Nb–Th 11–391 (8)
Nb–Ti 11–391 (8)
Nb–V 11–392 (8)
Nb–W 11–392 (7)
Nb–Y 11–392 (8)
Nb–Zr 11–392
Nb–Zn 11–393 (4)

Nd–Ni 11–393 (8)
Nd–Pr 11–394
Nd–Pt 11–394 (2)
Nd–Rh 11–395 (8)
Nd–Sb 11–395 (8)
Nd–Sc 11–396 (2)
Nd–Sn 11–396 (2)
Nd–Ti 11–397 (8)
Nd–Zn 11–397 (8)

Ni–O 11–398 (1)
Ni–P 11–398
Ni–Pb 11–398
Ni–Pd 11–399
Ni–Pr 11–399 (8)
Ni–Pt 11–400 (1)
Ni–Pu 11–401
Ni–Re 11–402 (1)
Ni–Rh 11–402
Ni–Ru 11–403
Ni–S 11–404
Ni–Sb 11–405
Ni–Si 11–405 (8)
Ni–Sm 11–406 (8)
Ni–Sn 11–407 (8)
Ni–Ta 11–408 (1)

Ni–Th 11–408 (3)
Ni–Ti 11–409 (1)
Ni–Tl 11–409
Ni–U 11–410
Ni–V 11–410 (8)
Ni–W 11–411 (8)
Ni–Y 11–411 (8)
Ni–Zn 11–411
Ni–Zr 11–412

Np–Pu 11–412 (8)
Np–U 11–413 (8)

O–Pu 11–413
O–Ti 11–414 (8)
O–V 11–414 (8)

Os–Ru 11–415
Os–Ti 11–415 (8)
Os–U 11–416
Os–W 11–416 (8)

P–Pd 11–416 (8)
P–Pt 11–417 (8)
P–Si 11–417
P–Sn 11–418
P–Tl 11–418
P–Zn 11–418 (8)

Pb–Pd 11–419 (8)
Pb–Pr 11–419 (8)
Pb–Pt 11–419
Pb–Pu 11–420 (8)
Pb–S 11–420
Pb–Sb 11–420 (8)
Pb–Se 11–421
Pb–Si 11–421
Pb–Sn 11–421 (8)
Pb–Sr 11–422
Pb–Te 11–422 (8)
Pb–Th 11–422
Pb–Ti 11–423 (8)
Pb–Tl 11–423
Pb–U 11–424 (1)
Pb–W 11–424 (8)
Pb–Y 11–425 (8)
Pb–Zn 11–425 (8)

Pd–Rh 11–426
Pd–S 11–426
Pd–Sb 11–427
Pd–Si 11–427 (8)
Pd–Sn 11–428
Pd–Ta 11–428 (8)
Pd–Te 11–429
Pd–Th 11–430
Pd–Ti 11–431 (8)
Pd–Tl 11–431 (8)
Pd–U 11–432 (8)
Pd–V 11–432
Pd–W 11–433
Pd–Y 11–433 (3)
Pd–Zn 11–434 (8)
Pd–Zr 11–434 (8)

Pr–Sn 11–435 (8)
Pr–Tl 11–435 (8)
Pr–Zn 11–436 (8)

Pt–Rh 11–436
Pt–Ru 11–437 (8)
Pt–Sb 11–437
Pt–Si 11–437
Pt–Sn 11–438 (8)
Pt–Te 11–438 (8)
Pt–Ti 11–439 (1)
Pt–Tl 11–439 (8)
Pt–V 11–440 (8)
Pt–W 11–440 (8)
Pt–Zr 11–441 (8)

Pu–Si 11–441
Pu–Th 11–442 (8)
Pu–Ti 11–442 (8)
Pu–U 11–443
Pu–Zn 11–444 (8)
Pu–Zr 11–445 (8)

Rb–S 11–445
Rb–Sb 11–446 (8)

Re–Rh 11–446
Re–Ru 11–447 (8)
Re–Si 11–447
Re–Tb 11–447 (8)
Re–U 11–448
Re–V 11–449
Re–W 11–450

Rh–Ta 11–450
Rh–U 11–451 (8)
Rh–V 11–451 (8)
Rh–W 11–452

Ru–Pt 11–453
Ru–W 11–453

S–Sb 11–454
S–Se 11–454
S–Sn 11–454
S–Te 11–455

Sb–Se 11–455
Sb–Si 11–455
Sb–Sn 11–456 (8)
Sb–Te 11–456
Sb–Tl 11–457
Sb–U 11–458 (8)
Sb–Zn 11–458 (4)
Sb–Zr 11–458

Sc–Ti 11–459
Sc–Y 11–459
Sc–Zr 11–459

Se–Sn 11–459
Se–Te 11–460 (8)
Se–Th 11–460 (8)
Se–Tl 11–460

Si–Sn 11–460
Si–Sr 11–461
Si–Te 11–461 (8)
Si–Th 11–462
Si–Ti 11–462 (8)
Si–Tl 11–463
Si–U 11–463 (8)
Si–V 11–463 (1)
Si–W 11–463 (8)
Si–Y 11–464
Si–Zn 11–465
Si–Zr 11–466 (8)

Sn–Sr 11–466
Sn–Te 11–466
Sn–Ti 11–467 (4)
Sn–Tl 11–467 (8)
Sn–U 11–468
Sn–V 11–468 (1)
Sn–Yb 11–469 (3)
Sn–Zn 11–469
Sn–Zr 11–470 (8)

Sr–Zn 11–470 (3)

Ta–Th 11–471 (8)
Ta–Ti 11–471 (1)
Ta–U 11–472 (8)
Ta–V 11–472 (8)
Ta–W 11–472 (8)
Ta–Y 11–473 (8)
Ta–Zr 11–473 (1)

Tc–V 11–474 (8)

Te–Tl 11–474
Te–Zn 11–474

Th–Ti 11–475 (8)
Th–U 11–475 (8)
Th–Y 11–475 (8)
Th–V 11–476
Th–Zn 11–476 (8)
Th–Zr 11–477

Ti–U 11–477 (8)
Ti–V 11–477 (8)
Ti–W 11–478 (8)
Ti–Y 11–478 (8)
Ti–Zn 11–478 (8)
Ti–Zr 11–479

Tl–Zn 11–479

U–V 11–480
U–W 11–480 (8)
U–Zn 11–480 (8)
U–Zr 11–481 (1)

V–W 11–481
V–Y 11–482 (8)
V–Zr 11–482 (8)

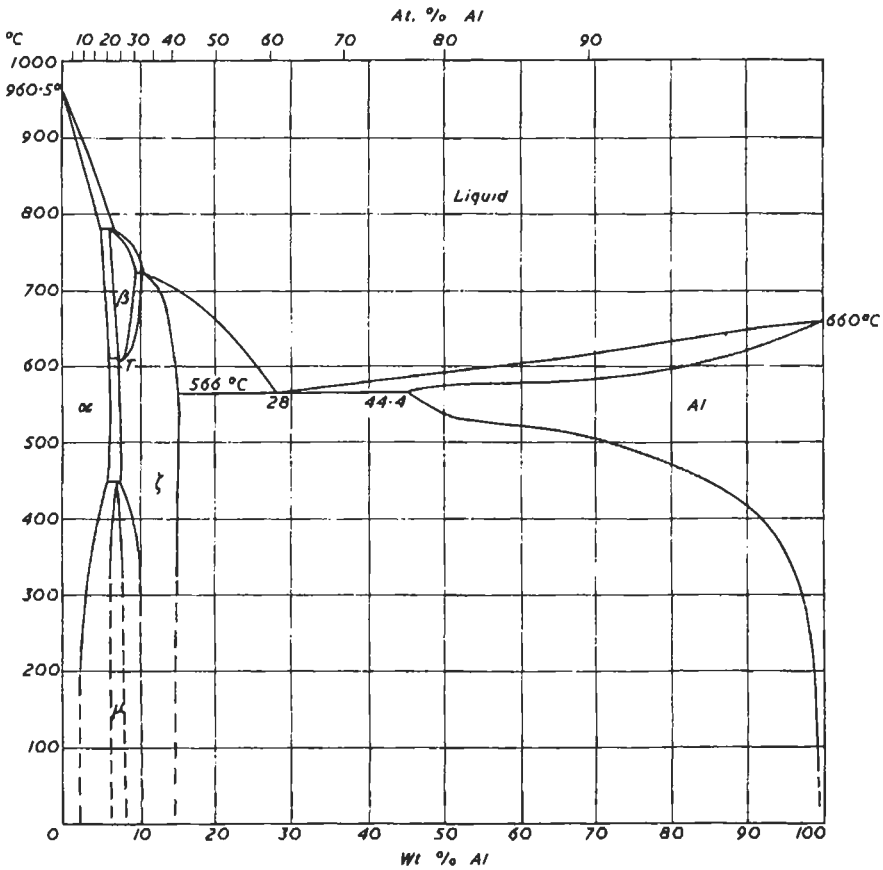
W–Zr 11–483 (8)

Y–Zn 11–484 (8)
Y–Zr 11–485

Zn–Zr 11–485 (8)

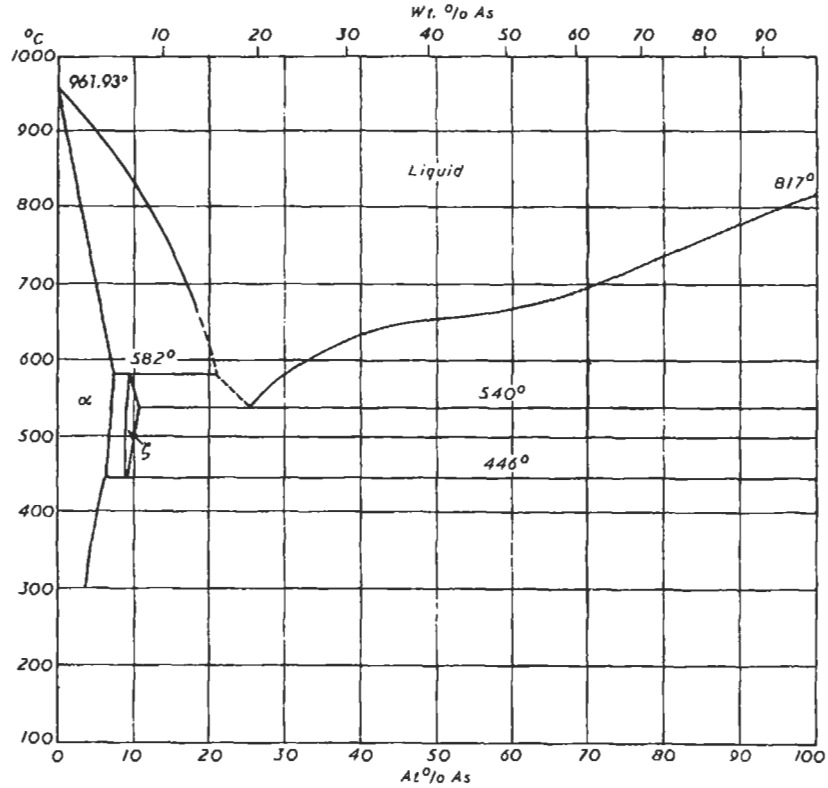
11.2 Equilibrium diagrams

References to individual diagrams are given at the end of this section. When no reference is given the reader should consult constitution of Binary Alloys by M. Hansen and K. Anderko, McGraw-Hill (1958) and the supplements by R. P. Elliott (1965) and F. A. Shunk (1969).

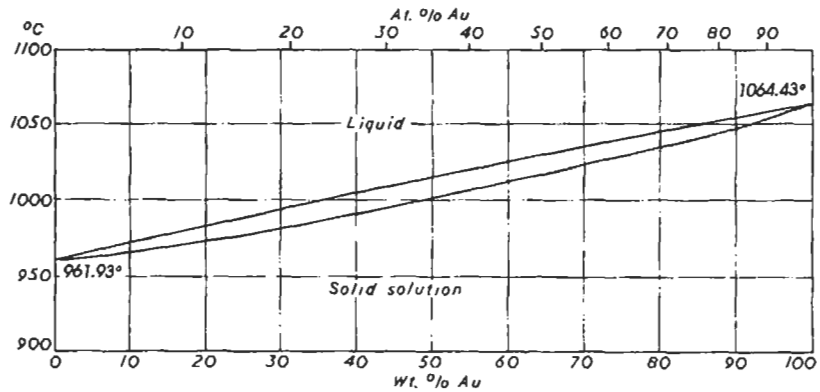


Ag–Al

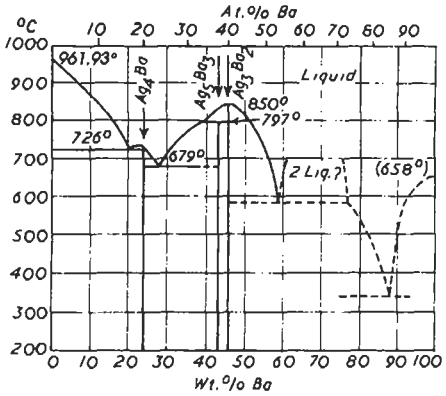
Ag–As


Wt. °/o As
°C
961.93°
Liquid
817°
582°
540°
α
ζ
446°
At°/o As

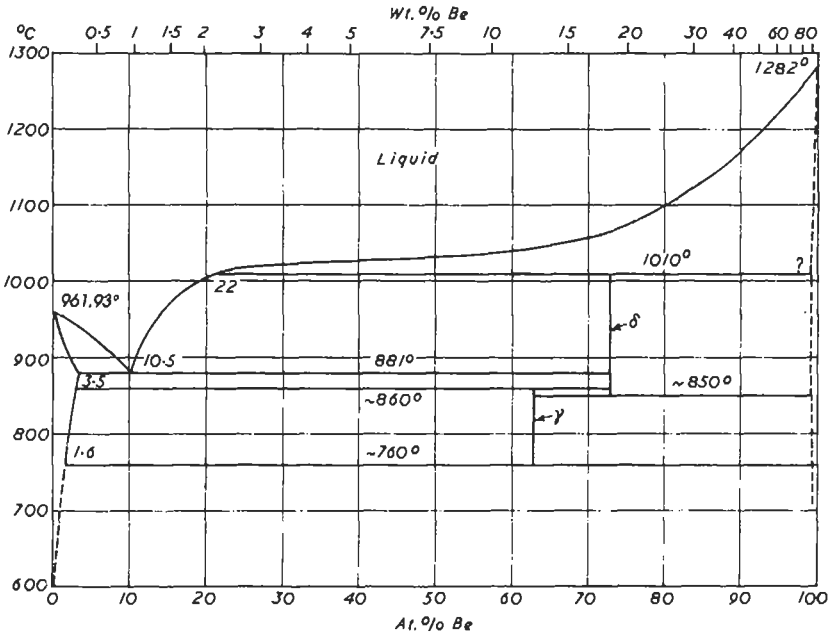
Ag–Au


At. °/o Au
°C
1064.43°
Liquid
961.93°
Solid solution
Wt. °/o Au

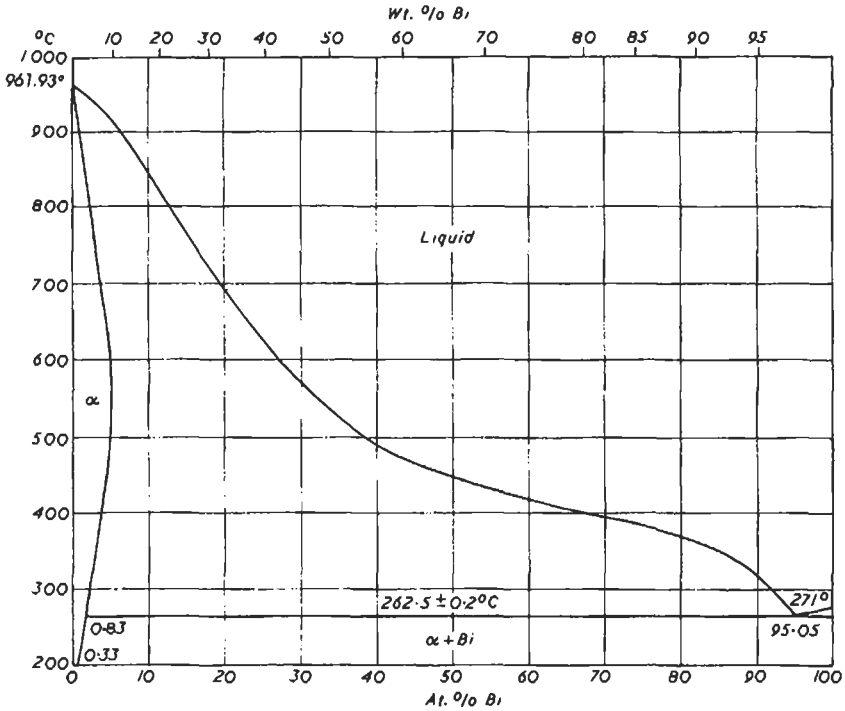
Ag–Ba


°C
At.% Ba
961.93°
Ag4Ba
Ag5Ba3
Ag3Ba2
Liquid
850°
797°
726°
679°
2 Liq.?
(658°)
Wt.% Ba

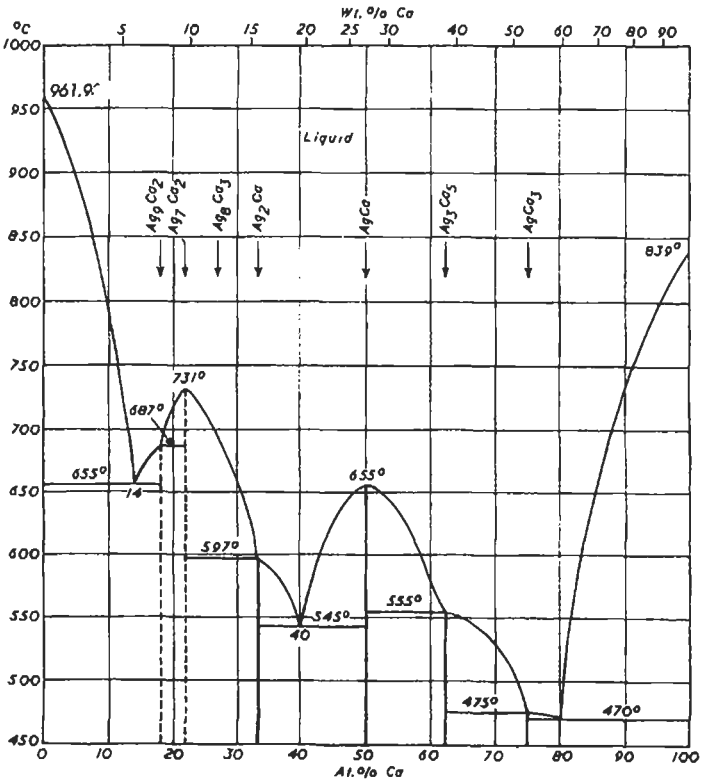
Ag–Be


°C
Wt.% Be
1282°
Liquid
1010°
961.93°
22
10·5
8810
~860°
3·5
~850°
δ
γ
1·6
~760°
At.% Be

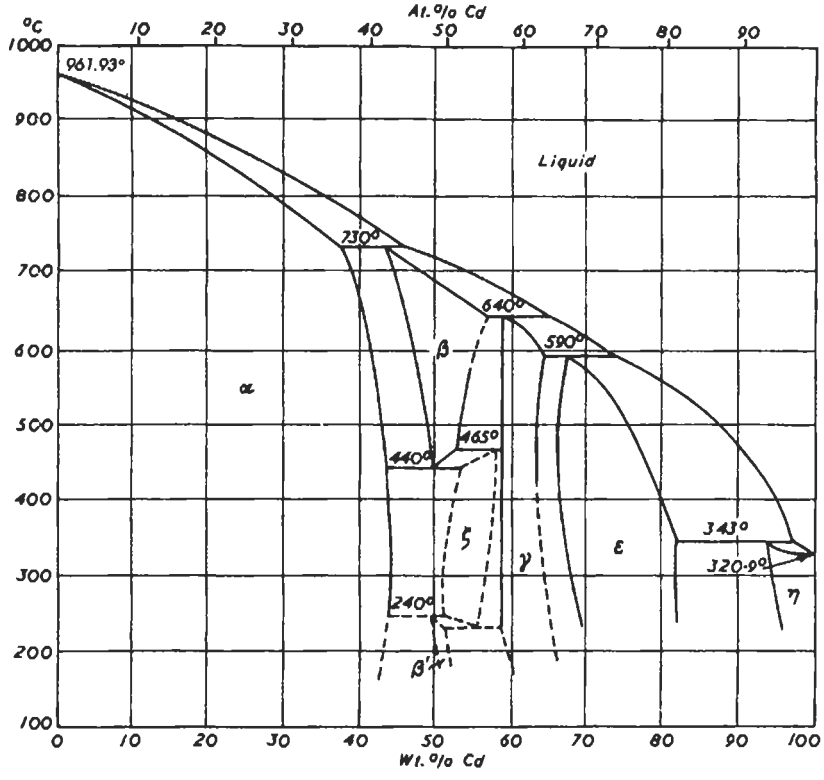
Ag–Bi


Wt. % Bi
°C
961.93°
Liquid
α
262·5 ± 0·2°C
271°
95·05
0·83
0·33
α + Bi
At. % Bi

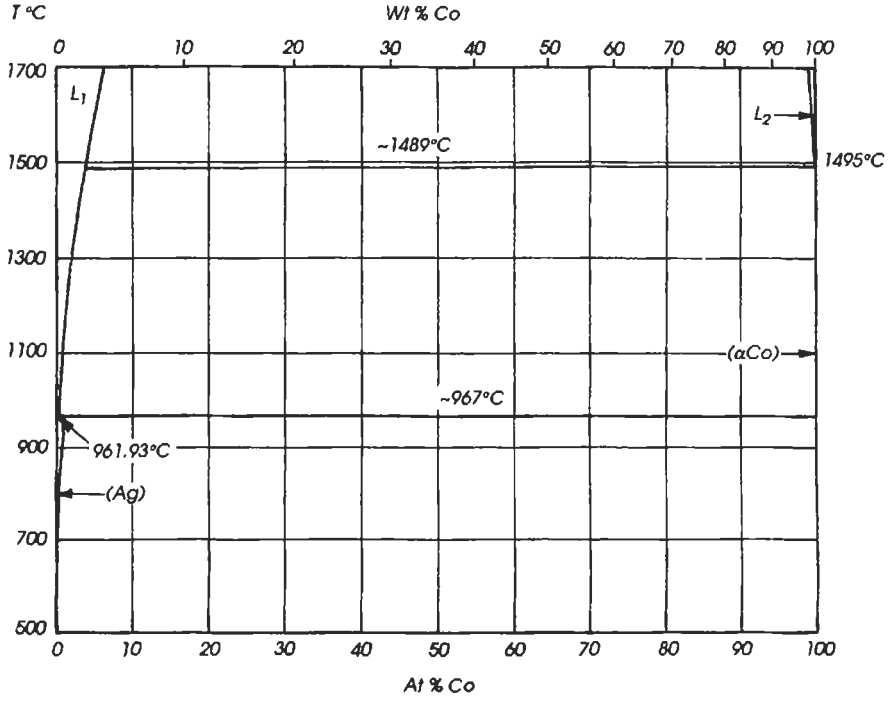
Ag–Ca


Wt. % Ca
°C
961.9°
Liquid
Ag9Ca2
Ag7Ca2
Ag8Ca3
Ag2Ca
AgCa
Ag3Ca5
AgCa3
839°
731°
687°
655°
14
597°
545°
40
655°
555°
475°
470°
At. % Ca

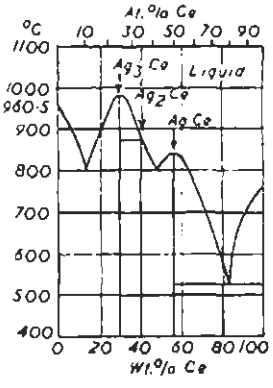
Ag–Cd


°C
At.% Cd
961.93°
Liquid
730°
640°
590°
β
α
465°
440°
343°
320·9°
ε
γ
η
ζ
240°
β'
Wt.% Cd

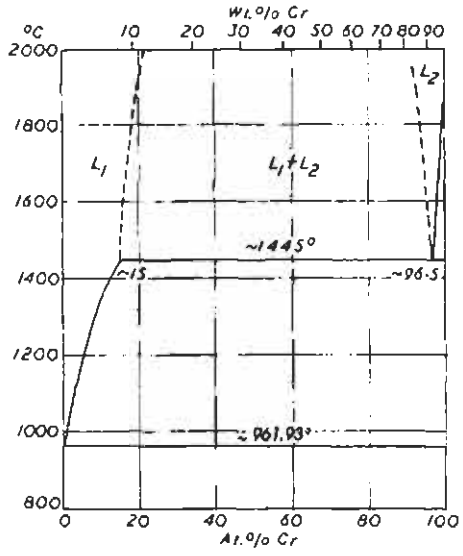
Ag–Co


T °C
Wt % Co
L1
L2
~1489°C
1495°C
(αCo)
~967°C
961.93°C
(Ag)
At % Co

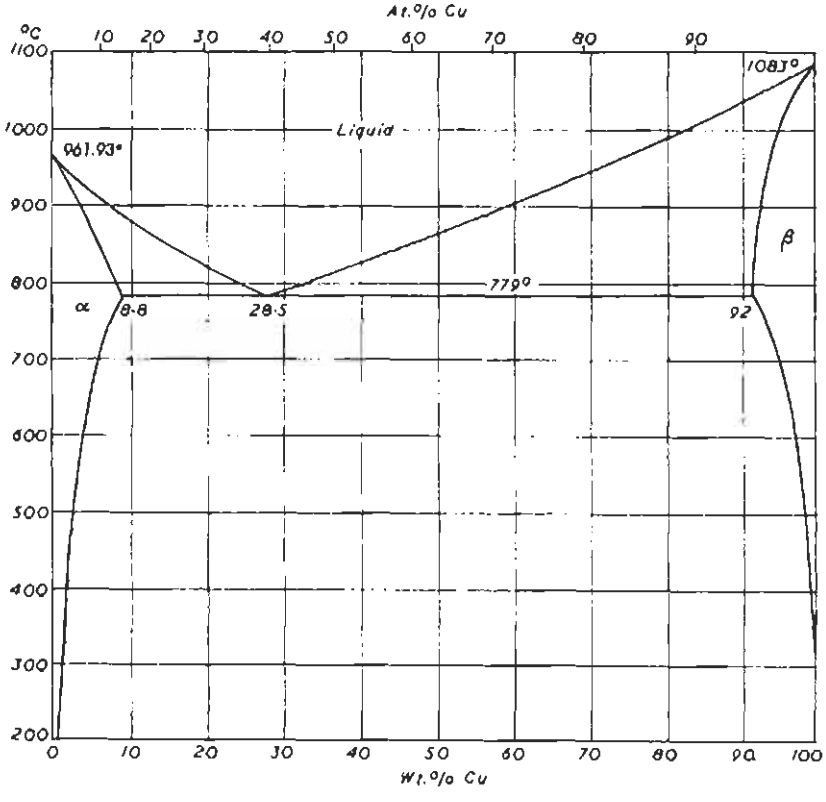
Ag–Ce



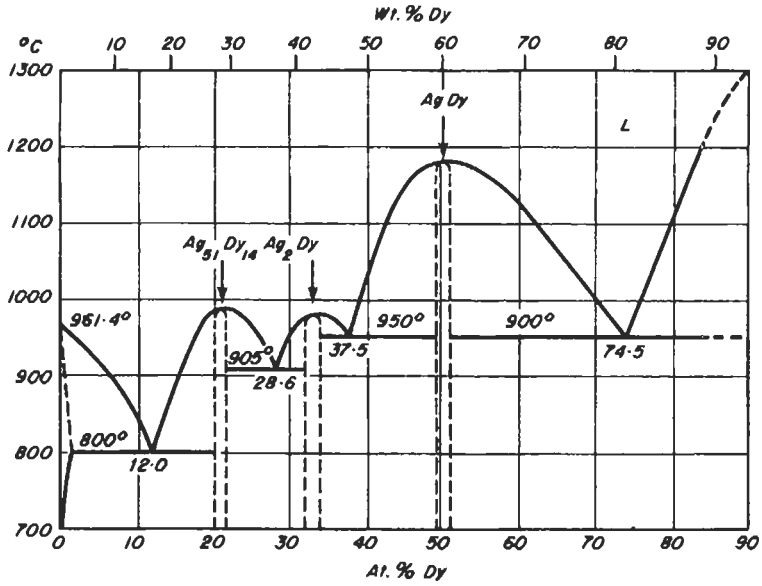
Ag–Cr



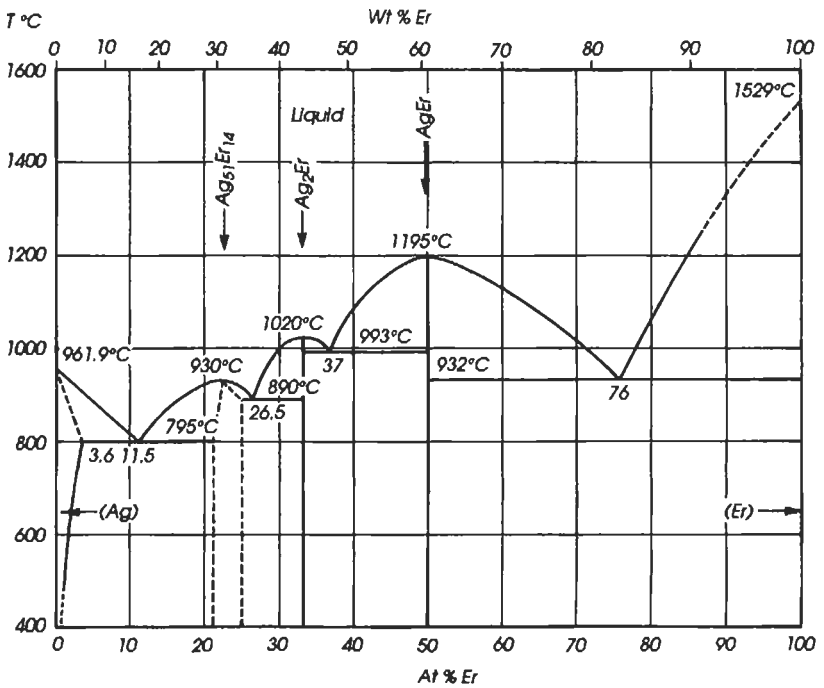
Ag–Cu



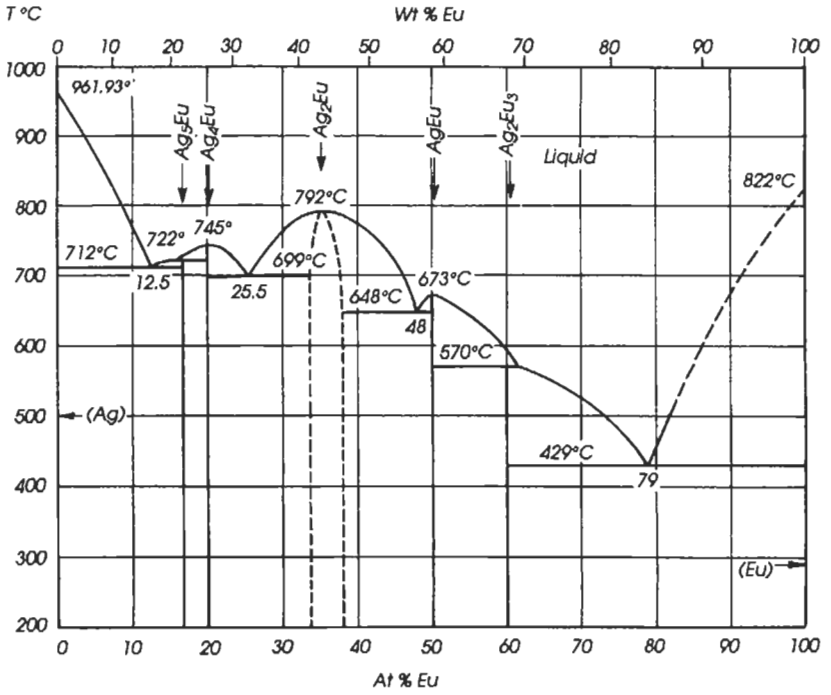
Ag–Dy


Wt. % Dy
°C
1300
1200
1100
1000
900
800
700
10
20
30
40
50
60
70
80
90
Ag Dy
L
$Ag_{51}Dy_{14}$
Ag_2Dy
961·4°
905°
28·6
950°
37·5
900°
74·5
800°
12·0
At. % Dy

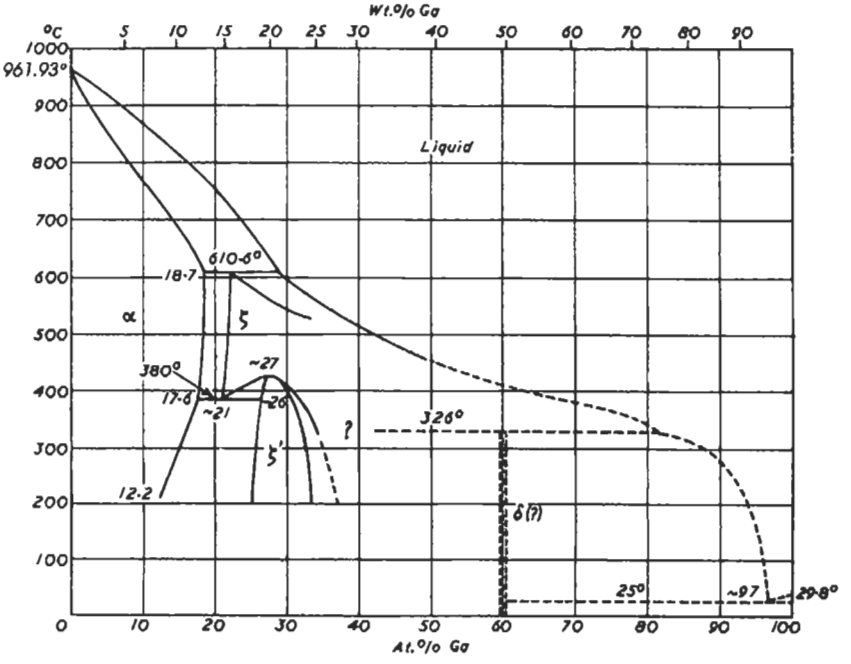
Ag–Er


T °C
Wt % Er
1600
1400
1200
1000
800
600
400
0
10
20
30
40
50
60
70
80
90
100
Liquid
$Ag_{51}Er_{14}$
Ag_2Er
AgEr
1529°C
1195°C
1020°C
993°C
961.9°C
930°C
37
932°C
890°C
26.5
795°C
76
3.6
11.5
(Ag)
(Er)
At % Er

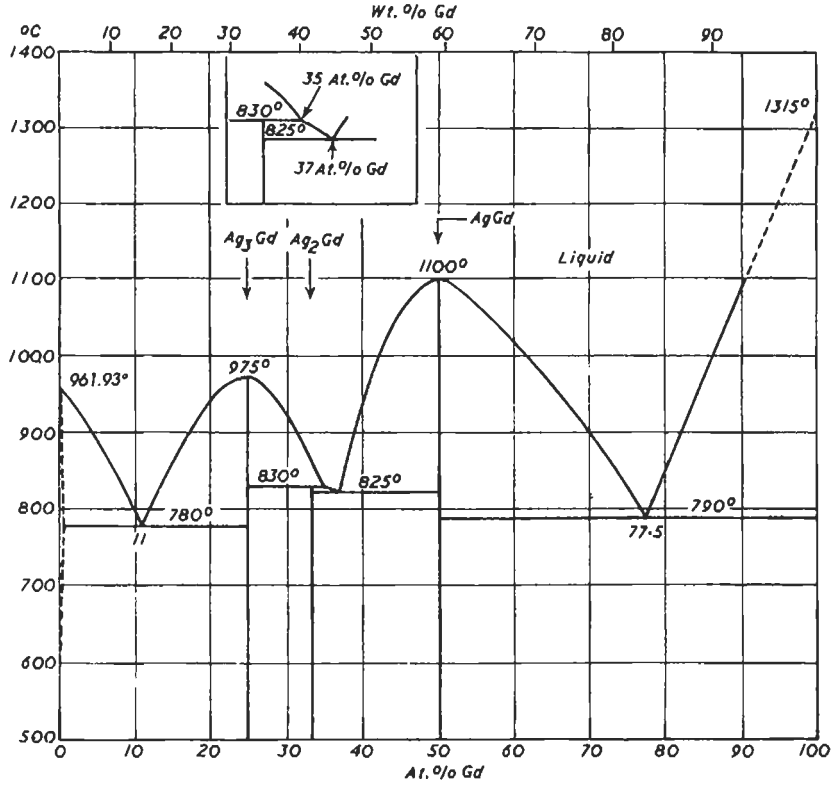
Ag–Eu


T °C
Wt % Eu
961.93°
Ag5Eu
Ag4Eu
Ag2Eu
AgEu
Ag2Eu3
Liquid
822°C
792°C
745°
722°
712°C
699°C
673°C
648°C
570°C
429°C
12.5
25.5
48
79
(Ag)
(Eu)
At % Eu

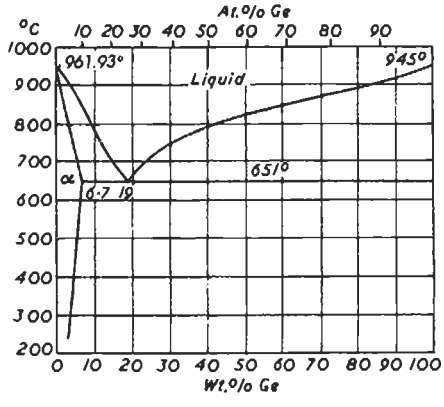
Ag–Ga


Wt.% Ga
°C
961.93°
Liquid
610-6°
18·7
α
ζ
380°
17·6
~27
~21
26
ζ'
?
12·2
326°
δ(?)
25°
~97
29·8°
At.% Ga

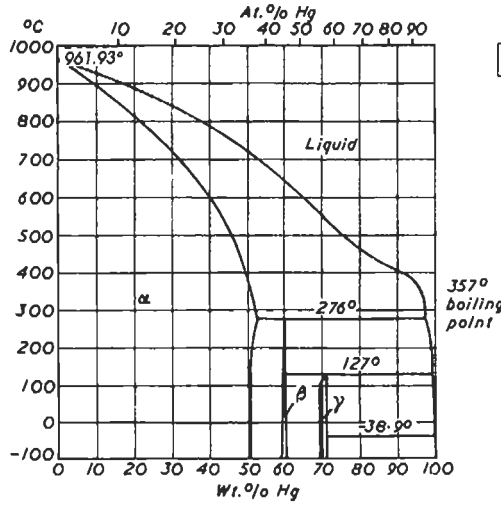
Ag–Gd



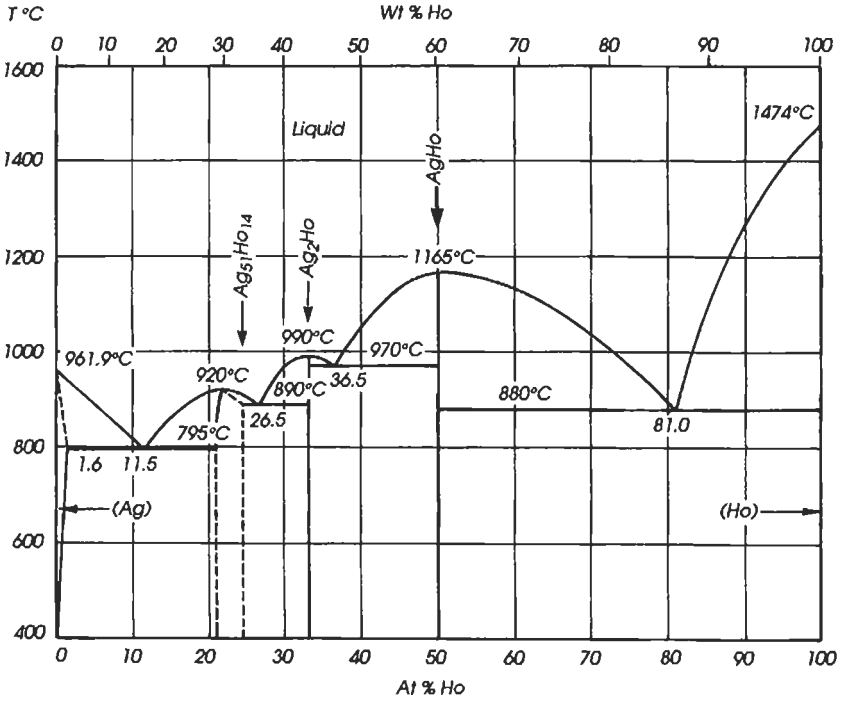
Ag–Ge



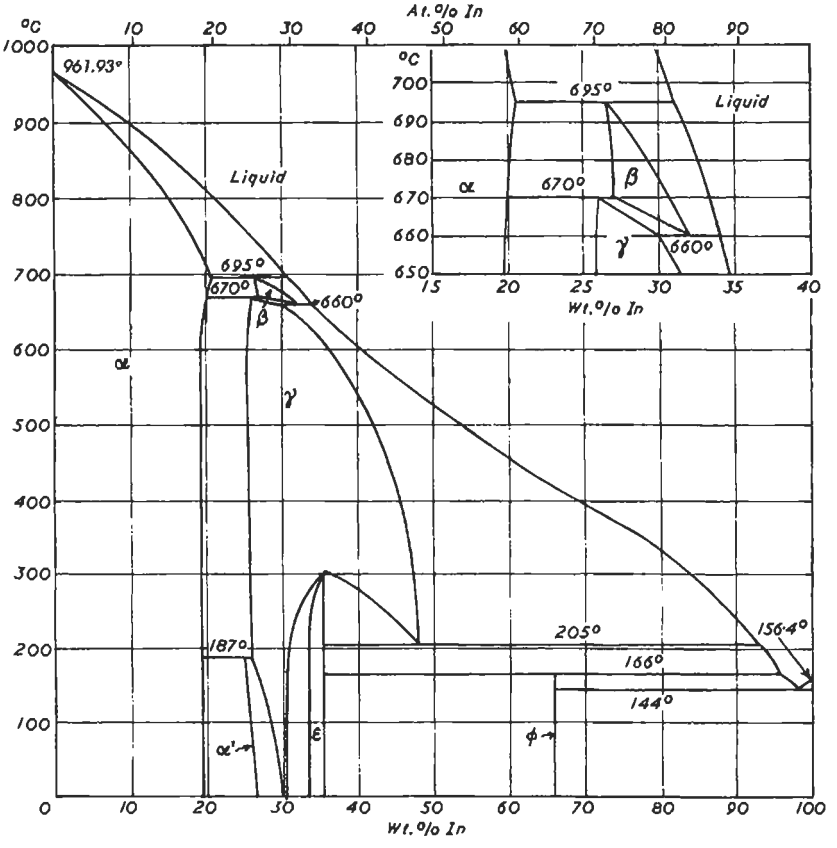
Ag–Hg



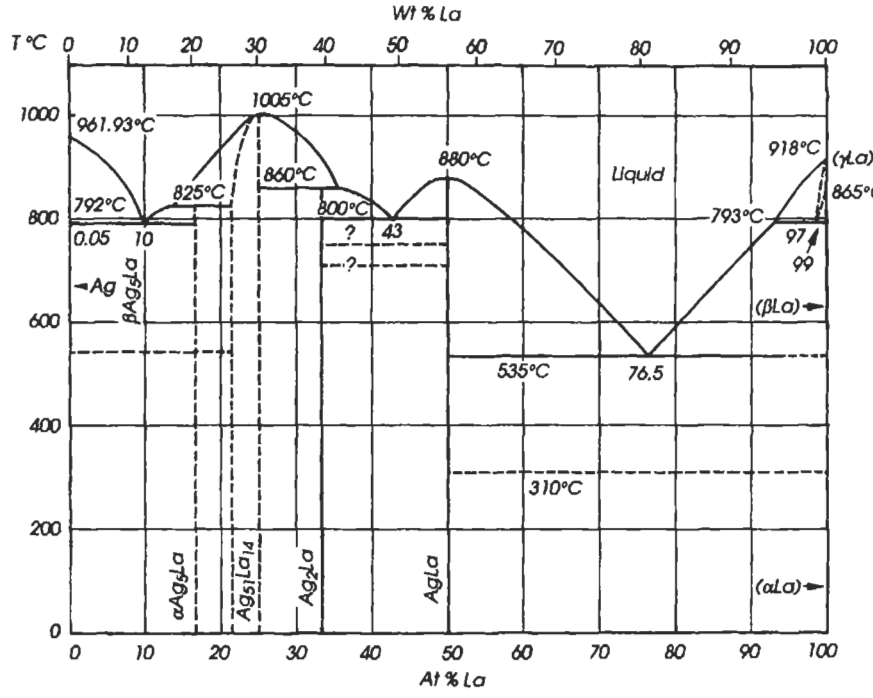
Ag–Ho


T °C
Wt % Ho
Liquid
1474°C
AgHo
1165°C
Ag51Ho14
Ag2Ho
990°C
970°C
961.9°C
920°C
890°C
36.5
880°C
26.5
795°C
81.0
1.6
11.5
(Ag)
(Ho)
At % Ho

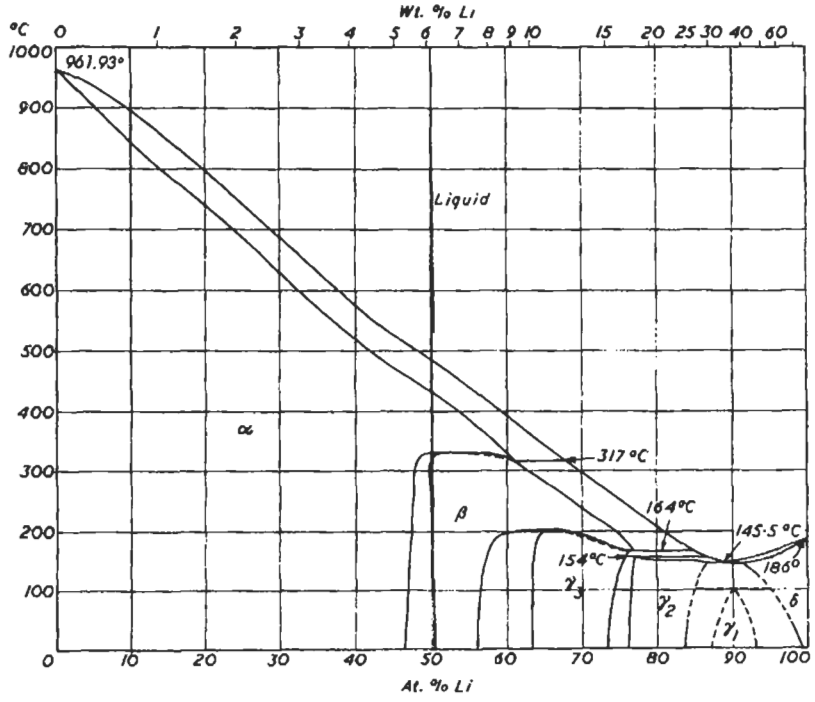
Ag–In


°C
At.% In
961.93°
Liquid
695°
670°
660°
α
β
γ
187°
205°
166°
156.4°
144°
α'
ε
φ
Wt.% In
Liquid
α
β
γ

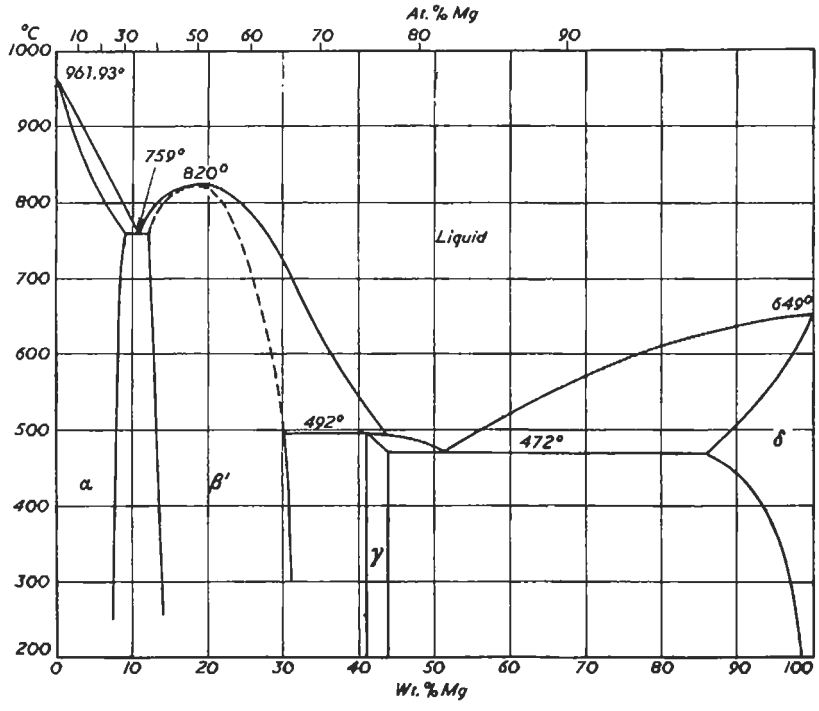
Ag–La


Wt % La
T °C
961.93°C
1005°C
825°C
860°C
880°C
800°C
792°C
918°C
(γLa)
865°C
Liquid
793°C
0.05
10
43
97
99
βAg5La
Ag
(βLa)
535°C
76.5
310°C
αAg5La
Ag51La14
Ag2La
AgLa
(αLa)
At % La

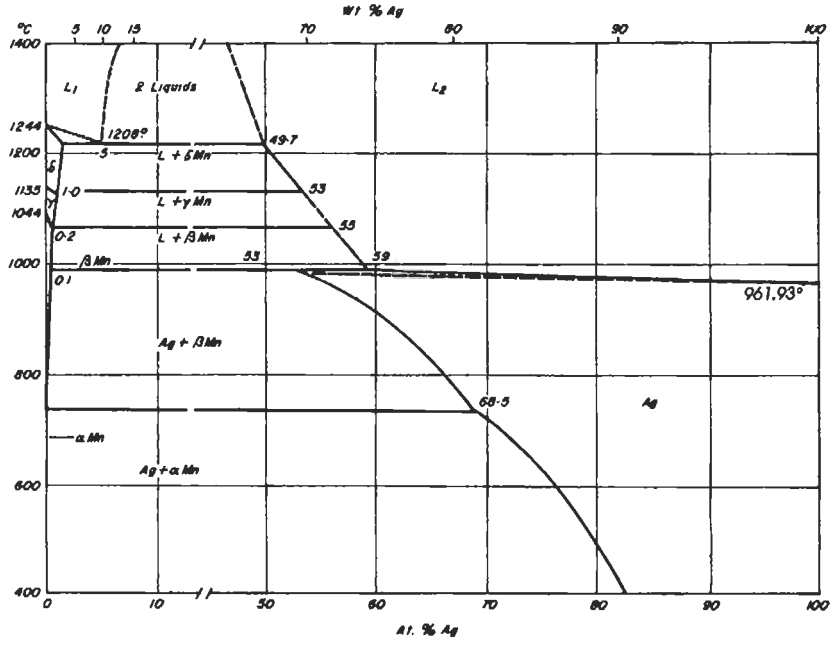
Ag–Li


Wt. % Li
°C
961.93°
Liquid
α
317 °C
β
164°C
145.5 °C
154°C
186°
γ3
γ2
γ1
δ
At. % Li

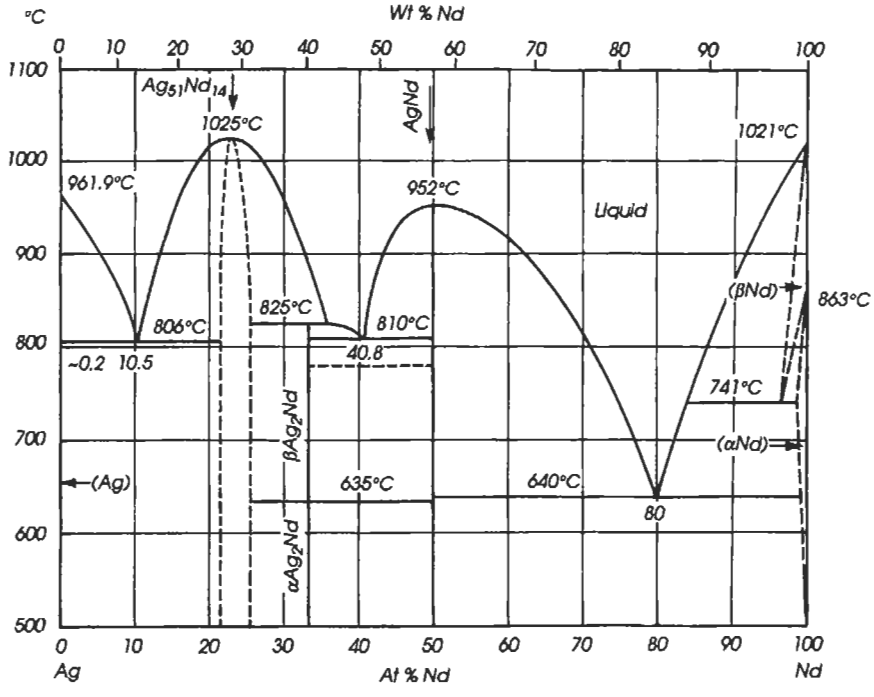
Ag–Mg


At. % Mg
°C
961.93°
759°
820°
Liquid
649°
492°
472°
α
β′
γ
δ
Wt. % Mg

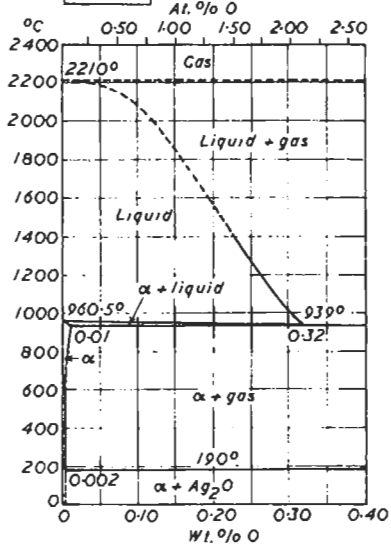
Ag–Mn


Wt % Ag
°C
L1
2 Liquids
L2
1208°
49·7
L + δ Mn
L + γ Mn
L + β Mn
β Mn
961,93°
Ag + β Mn
68·5
Ag
α Mn
Ag + α Mn
At. % Ag

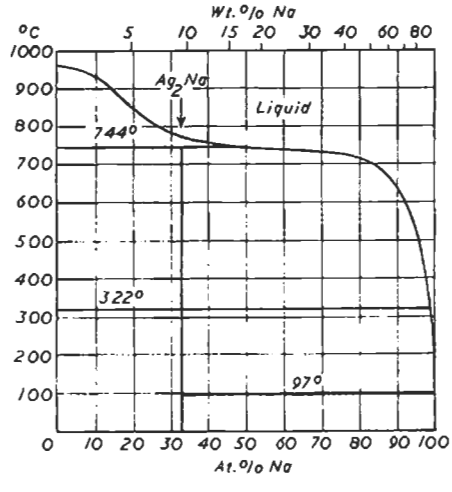
Ag–Nd



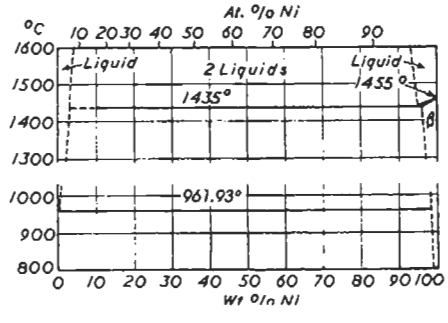
Ag–O



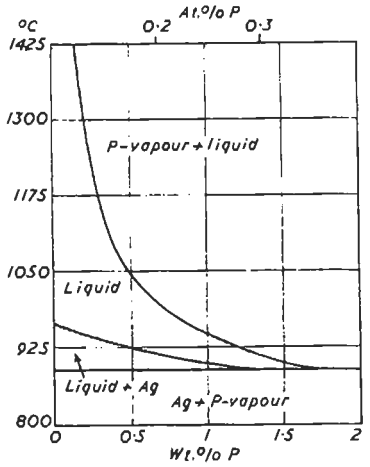
Ag–Na



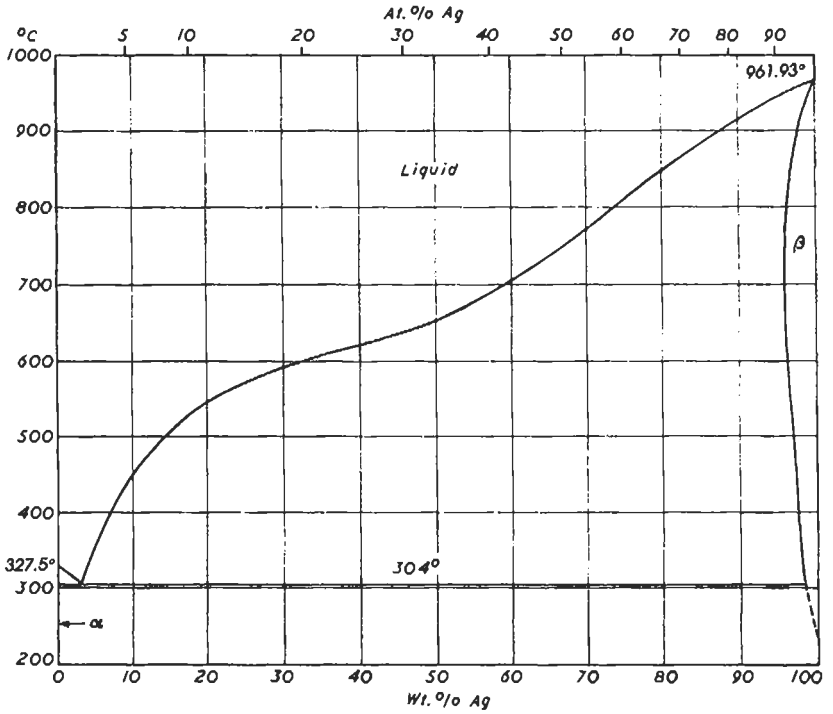
Ag–Ni



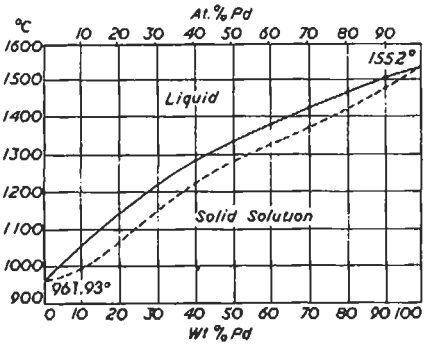
Ag–P



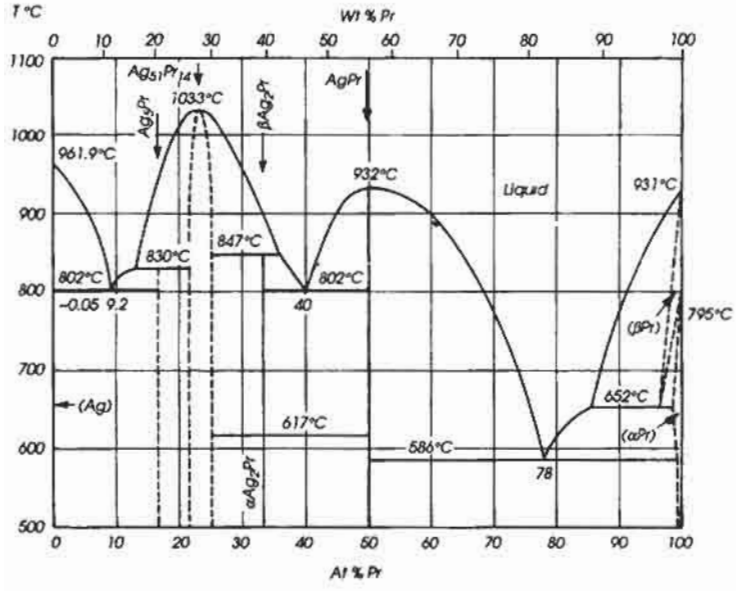
Ag–Pb



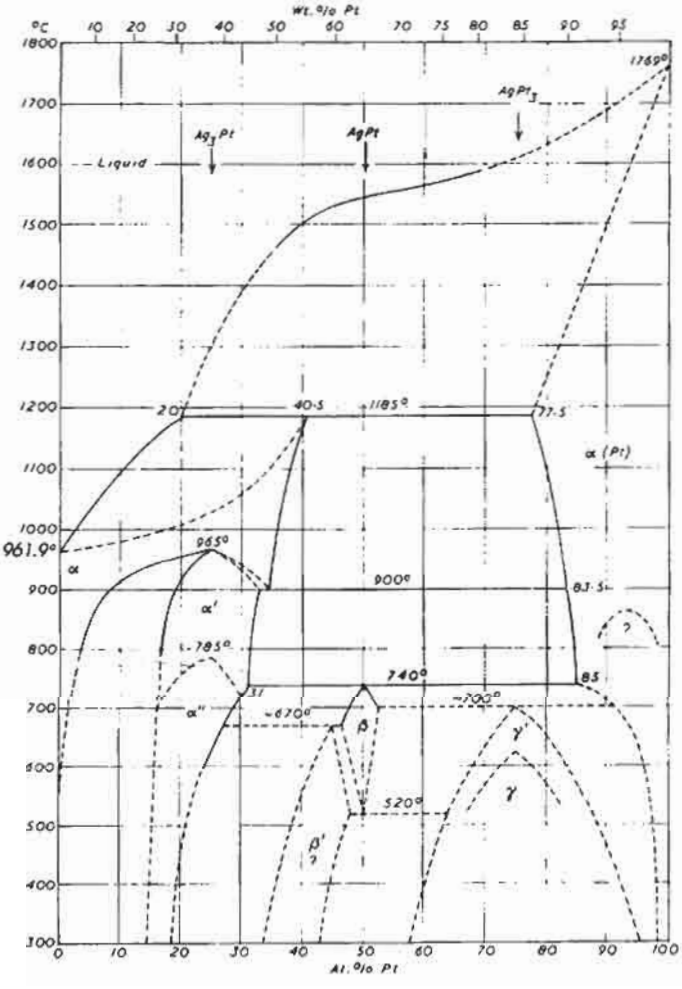
Ag–Pd



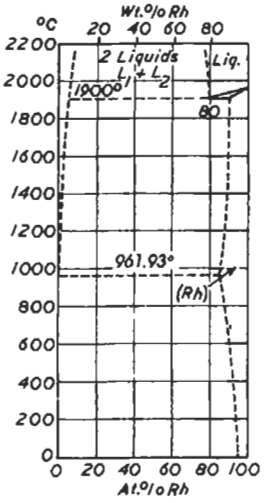
Ag–Pr


T °C
Wt % Pr
At % Pr
1100
1000
900
800
700
600
500
961.9°C
802°C
830°C
1033°C
847°C
802°C
932°C
931°C
795°C
652°C
617°C
586°C
Liquid
(Ag)
(βPr)
(αPr)
-0.05
9.2
40
78

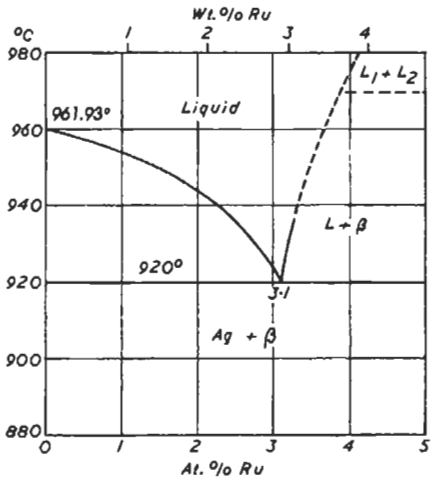
Ag–Pt


°C
Wt. % Pt
At. % Pt
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
961.9°
1769°
Liquid
20
40·5
1185°
77·5
965°
900°
83·5
740°
85
α
α'
α''
β
β'
γ
γ'
α (Pt)
520°

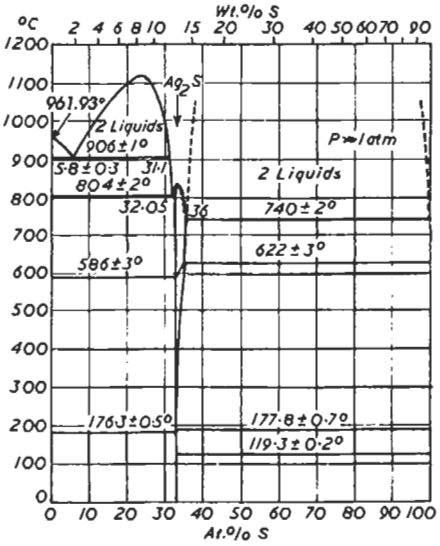
Ag–Rh



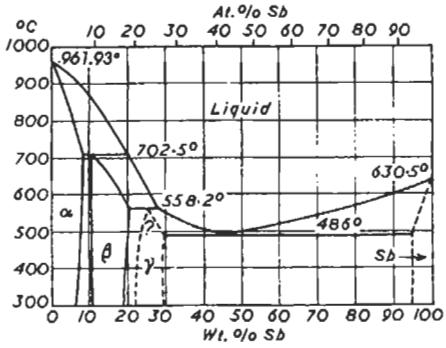
Ag–Ru



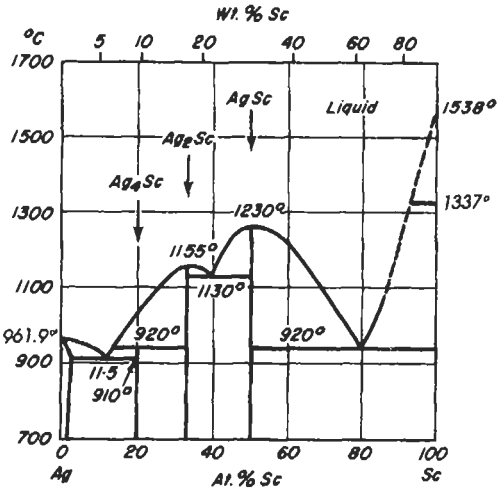
Ag–S



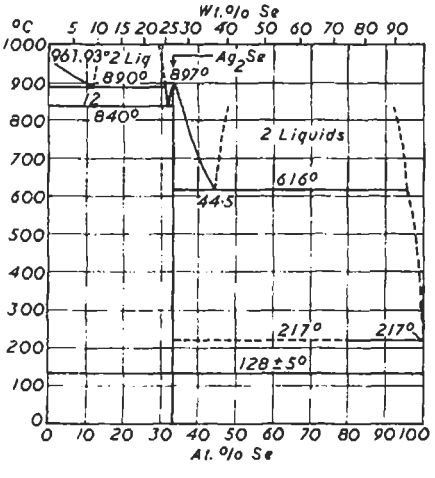
Ag–Sb



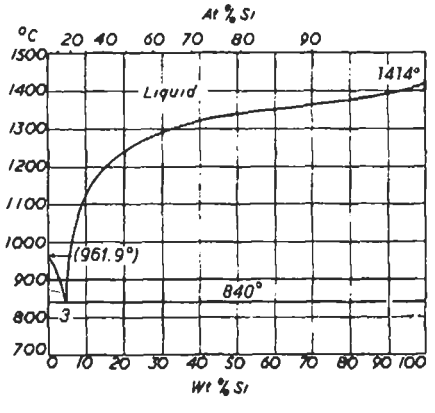
Ag–Sc



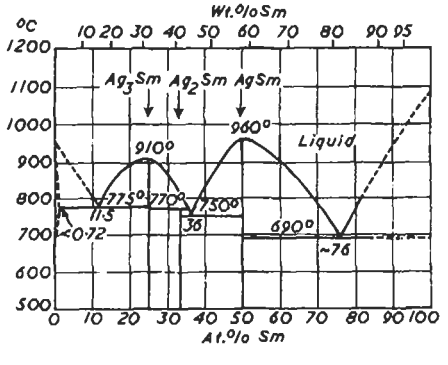
Ag–Se



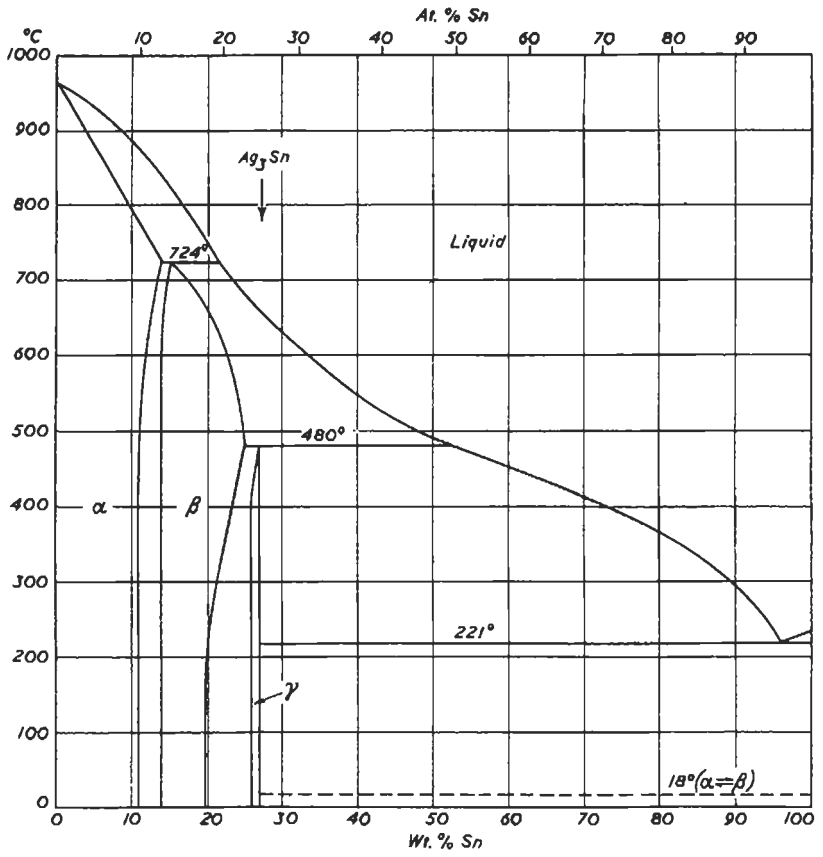
Ag–Si



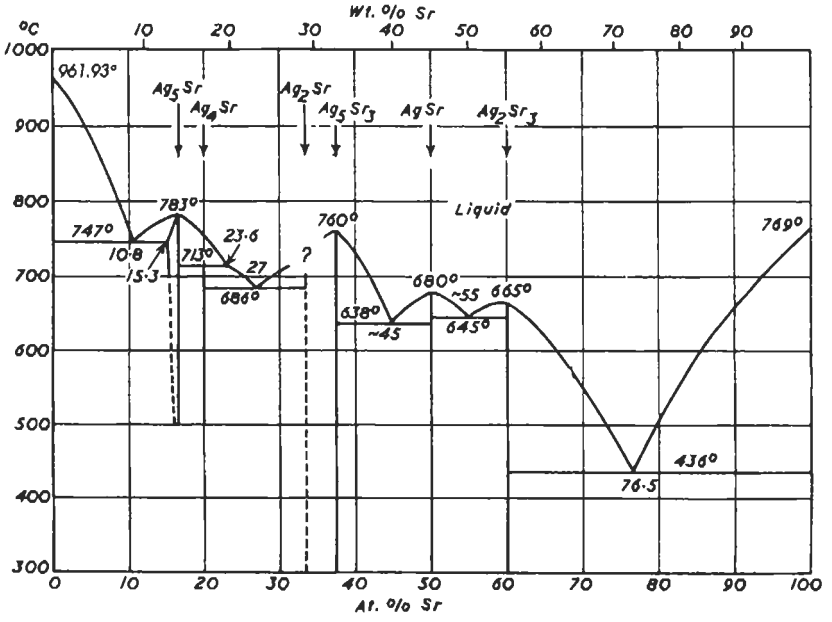
Ag–Sm



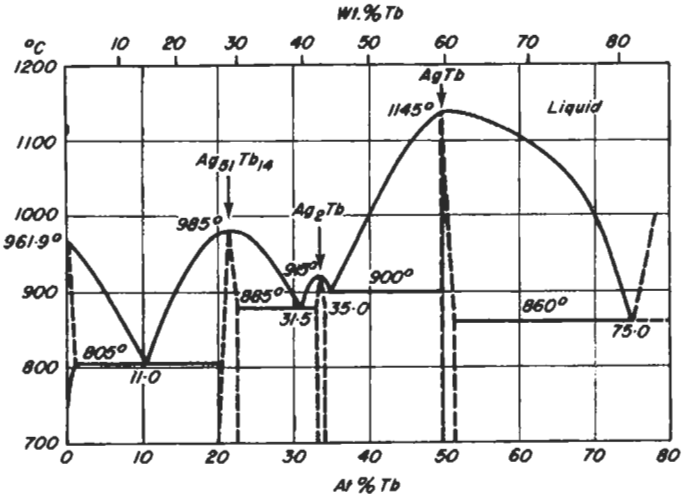
Ag–Sn


At. % Sn
°C
Ag3Sn
724°
Liquid
480°
α
β
221°
γ
18°(α⇌β)
Wt. % Sn

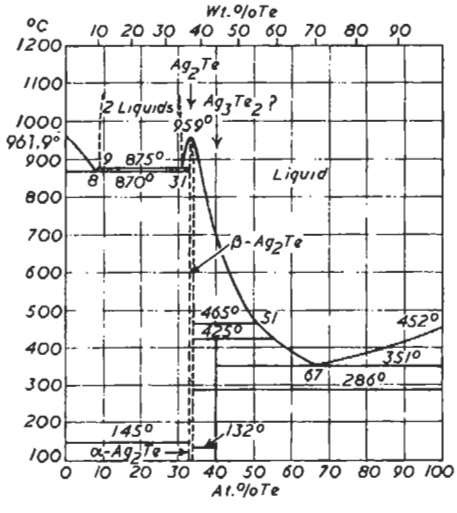
Ag–Sr


Wt. % Sr
°C
961.93°
Ag5Sr
Ag4Sr
Ag2Sr
Ag5Sr3
AgSr
Ag2Sr3
783°
747°
10·8
15·3
713°
23·6
27
686°
?
760°
Liquid
769°
680°
~55
665°
638°
~45
645°
436°
76·5
At. % Sr

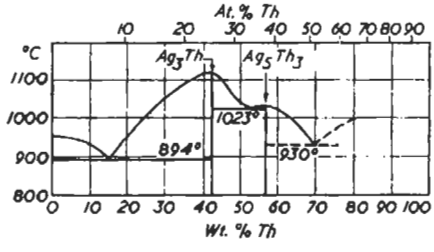
Ag–Tb



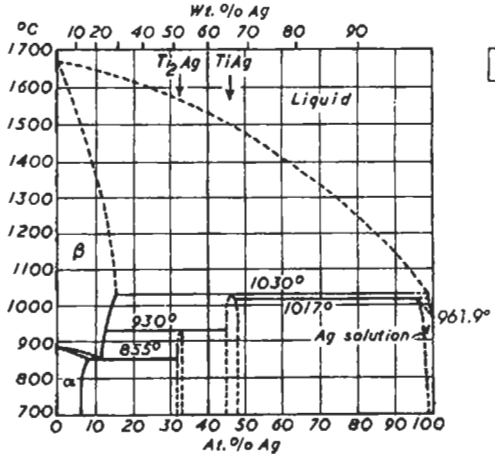
Ag–Te



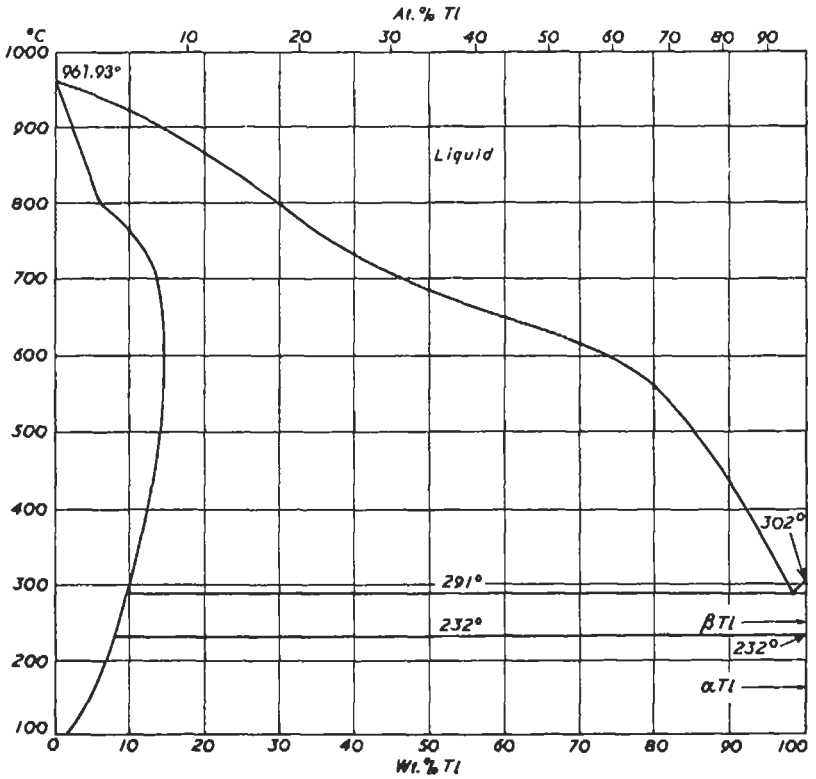
Ag–Th



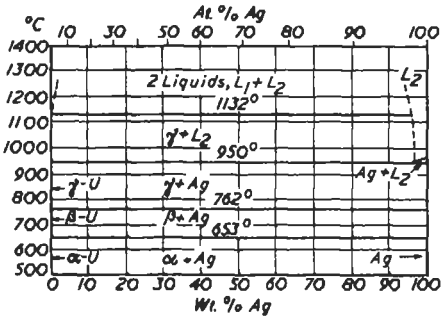
Ag–Ti



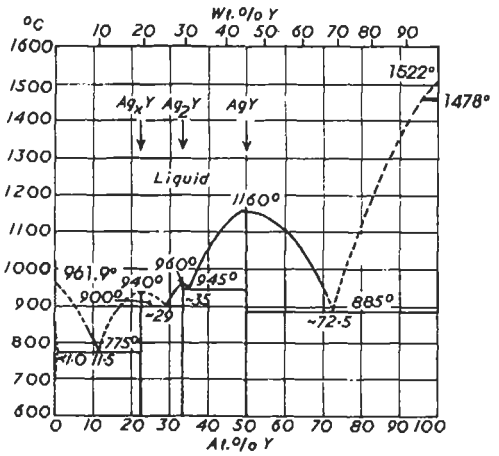
Ag–Tl


At. % Tl
°C
961.93°
Liquid
302°
291°
232°
βTl
232°
αTl
Wt. % Tl

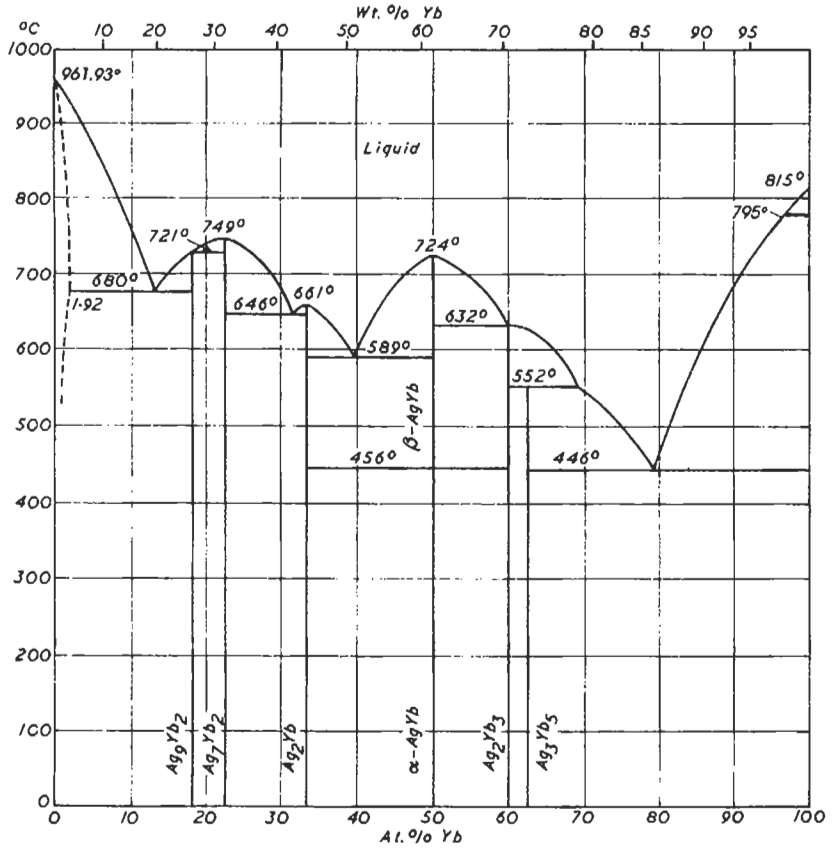
Ag–U


At % Ag
°C
2 Liquids, L1 + L2
1132°
L2
γ + L2
950°
Ag + L2
γ-U
γ + Ag
762°
β-U
β + Ag
657°
α-U
α + Ag
Ag
Wt. % Ag

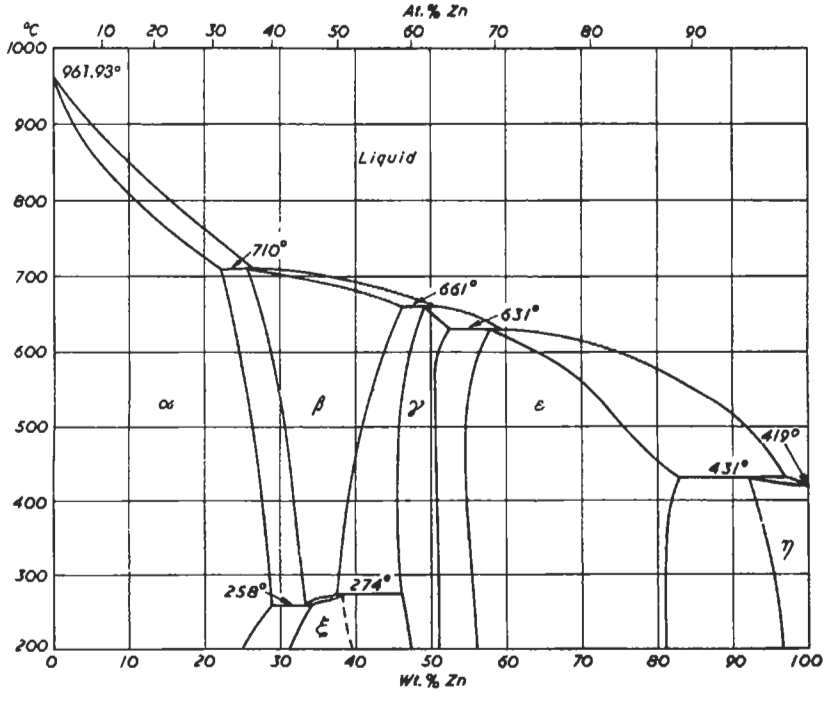
Ag–Y


Wt. % Y
°C
1522°
1478°
AgxY
Ag2Y
AgY
Liquid
1160°
961.9°
960°
940°
945°
900°
~29
~35
885°
~72·5
775°
41·0
11·5
At. % Y

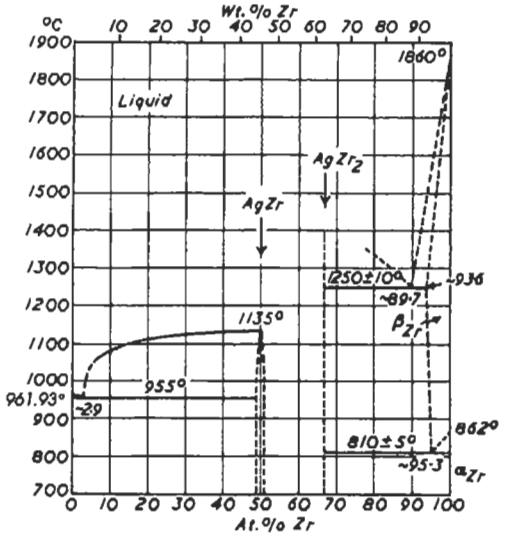
Ag–Yb

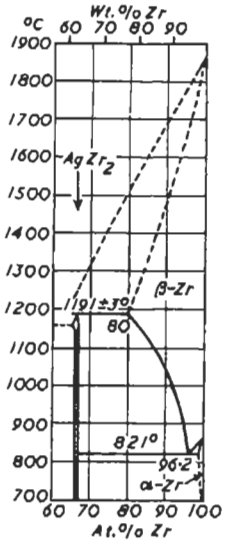

°C
Wt. % Yb
961.93°
Liquid
815°
795°
721°
749°
724°
680°
1·92
646°
661°
632°
589°
552°
β–AgYb
456°
446°
Ag99Yb2
Ag7Yb2
Ag2Yb
α–AgYb
Ag2Yb3
Ag3Yb5
At. % Yb

Ag–Zn


°C
At. % Zn
961.93°
Liquid
710°
661°
631°
α
β
γ
ε
η
419°
431°
258°
274°
ζ
Wt. % Zn

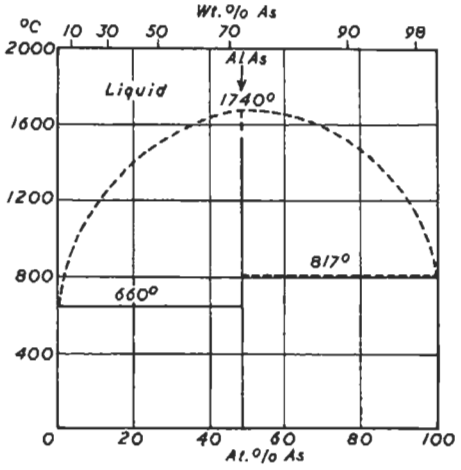
Ag–Zr



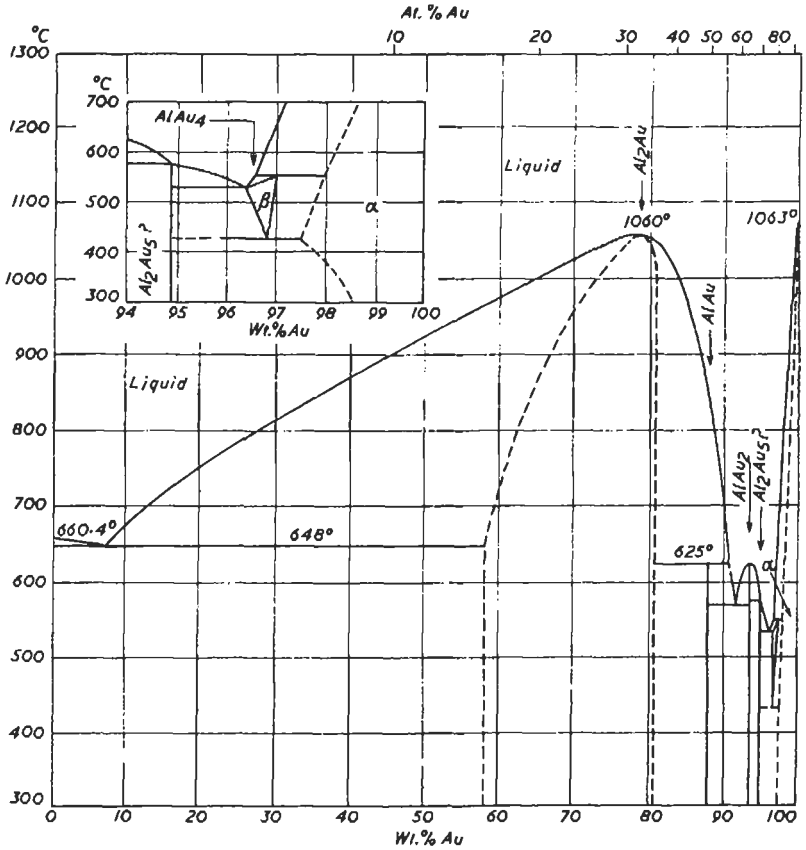


Ag–Zr

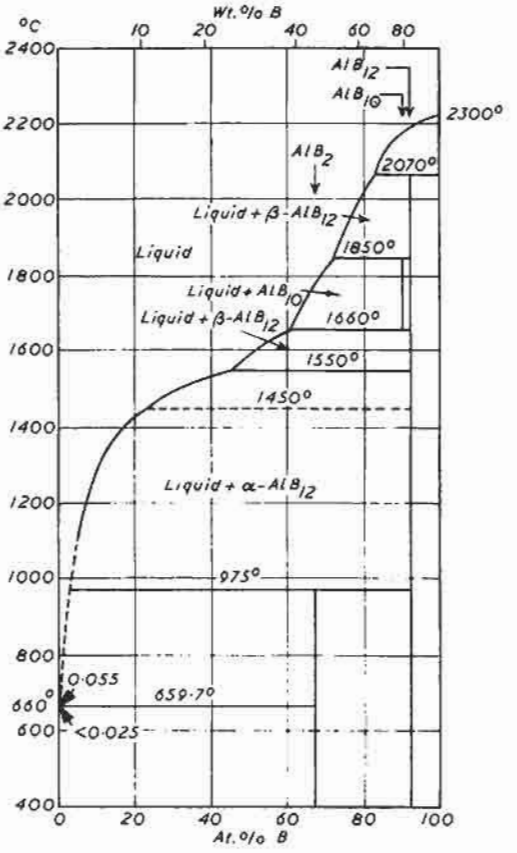
Al–As



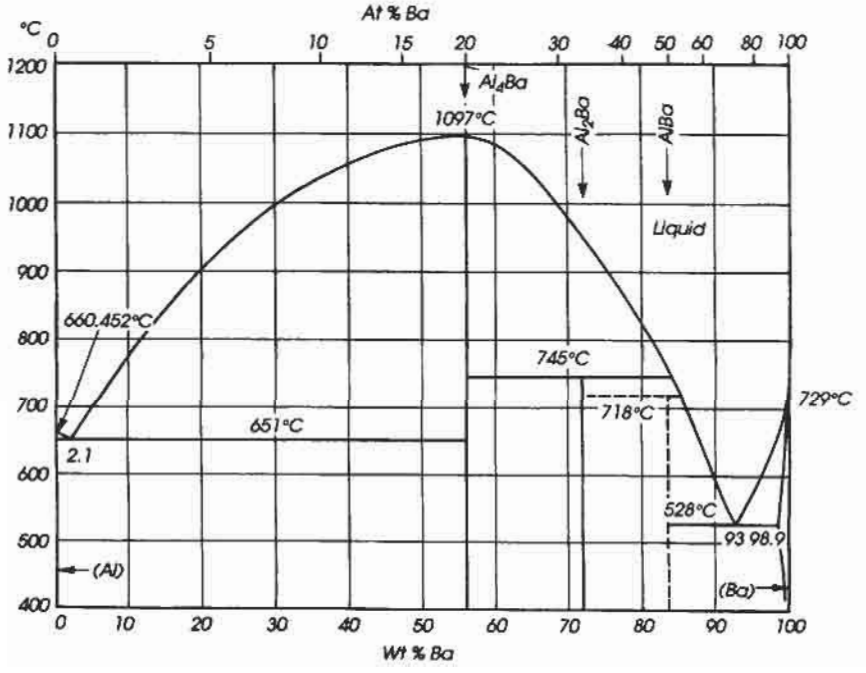
Al–Au


At. % Au
°C
Liquid
Al2Au
1060°
1063°
Al Au
Al Au2
Al2Au5 ?
660.4°
648°
625°
α
Wt. % Au
AlAu4
β
α
Al2Au5 ?
Wt. % Au

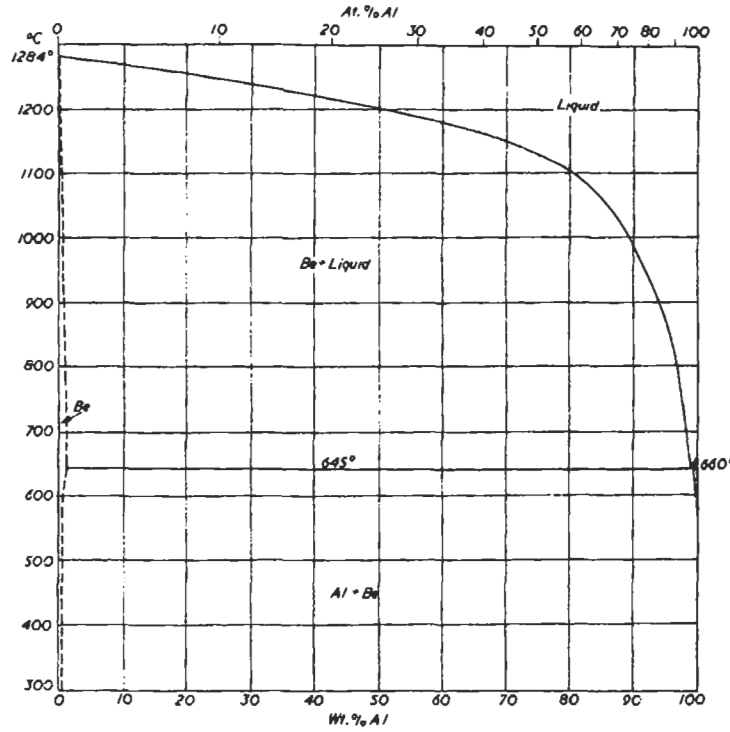
Al–B


°C
Wt. % B
10
20
40
60
80
2400
2200
2000
1800
1600
1400
1200
1000
800
660°
600
400
AlB12
AlB10
2300°
AlB2
2070°
Liquid + β-AlB12
1850°
Liquid
Liquid + AlB10
Liquid + β-AlB12
1660°
1550°
1450°
Liquid + α-AlB12
975°
0·055
659·7°
<0·025
0
20
40
60
80
100
At. % B

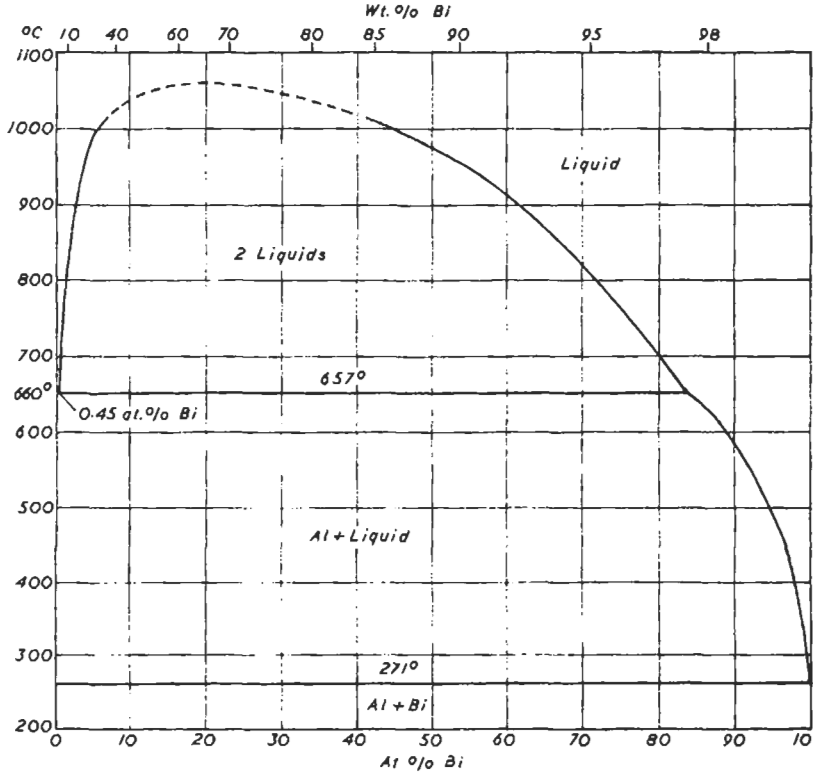
Al–Ba


At % Ba
°C
0
5
10
15
20
30
40
50
60
80
100
1200
1100
1000
900
800
700
600
500
400
Al4Ba
1097°C
Al2Ba
AlBa
Liquid
660.452°C
745°C
718°C
729°C
651°C
2.1
528°C
93 98.9
(Al)
(Ba)
0
10
20
30
40
50
60
70
80
90
100
Wt % Ba

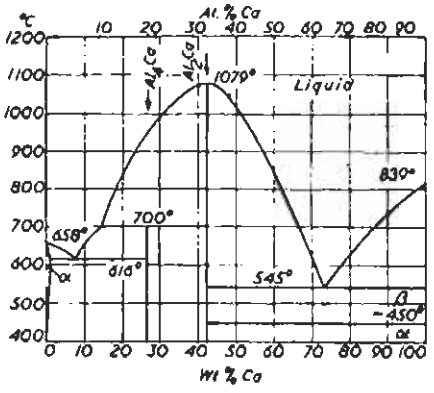
Al–Be


At. % Al
°C
1284°
Liquid
Be + Liquid
Be
645°
660°
Al + Be
Wt. % Al

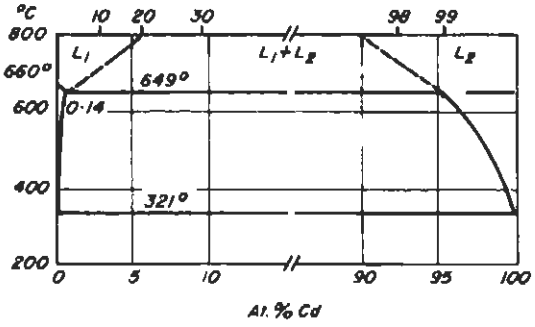
Al–Bi


Wt. % Bi
°C
Liquid
2 Liquids
657°
660°
0·45 at. % Bi
Al + Liquid
271°
Al + Bi
At % Bi

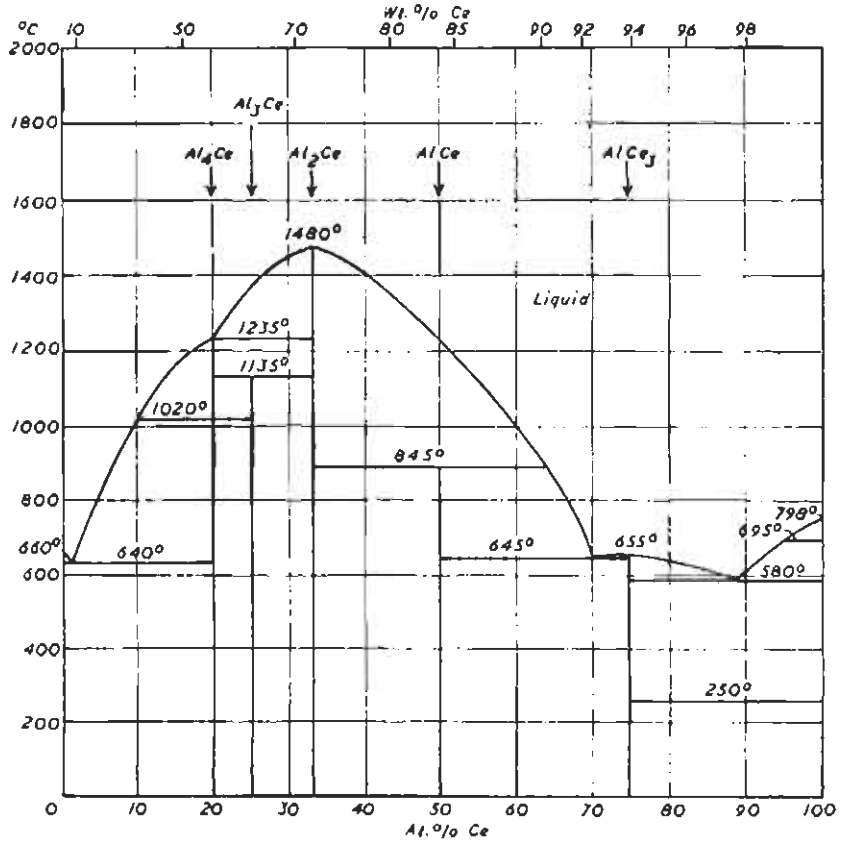
Al–Ca



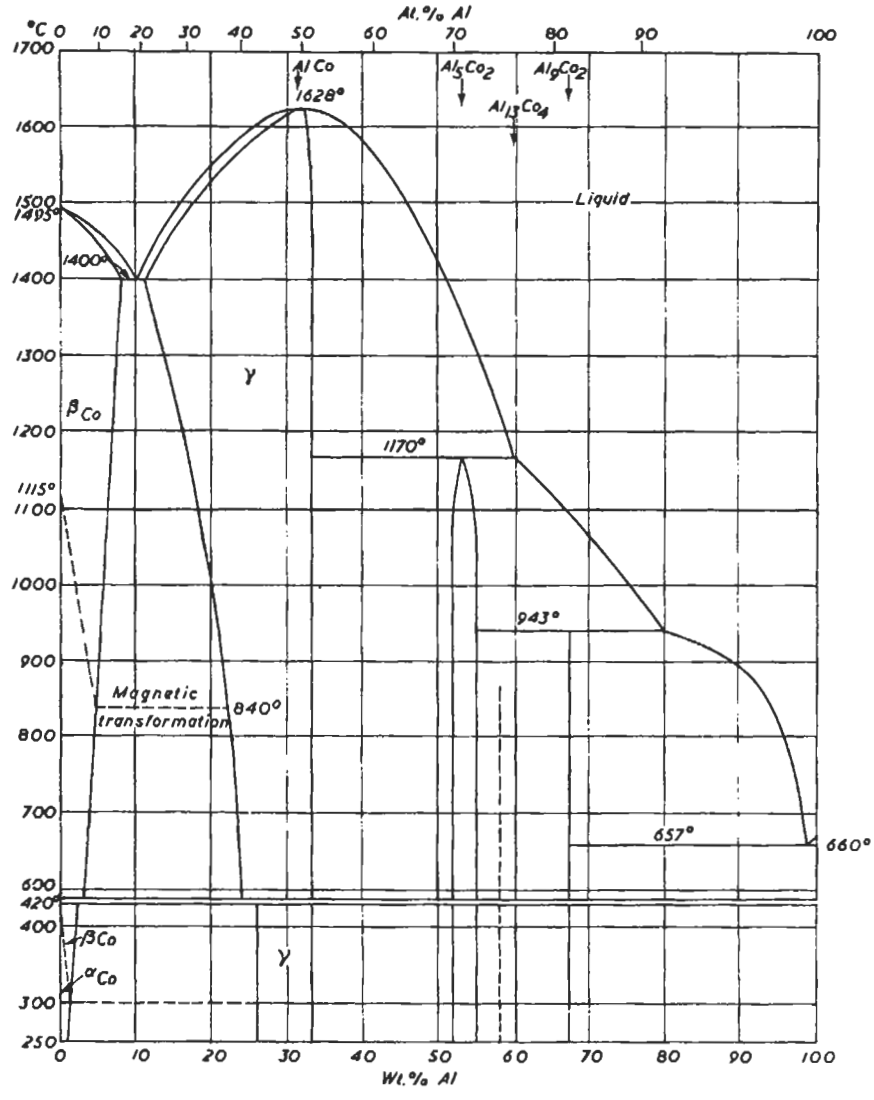
Al–Cd



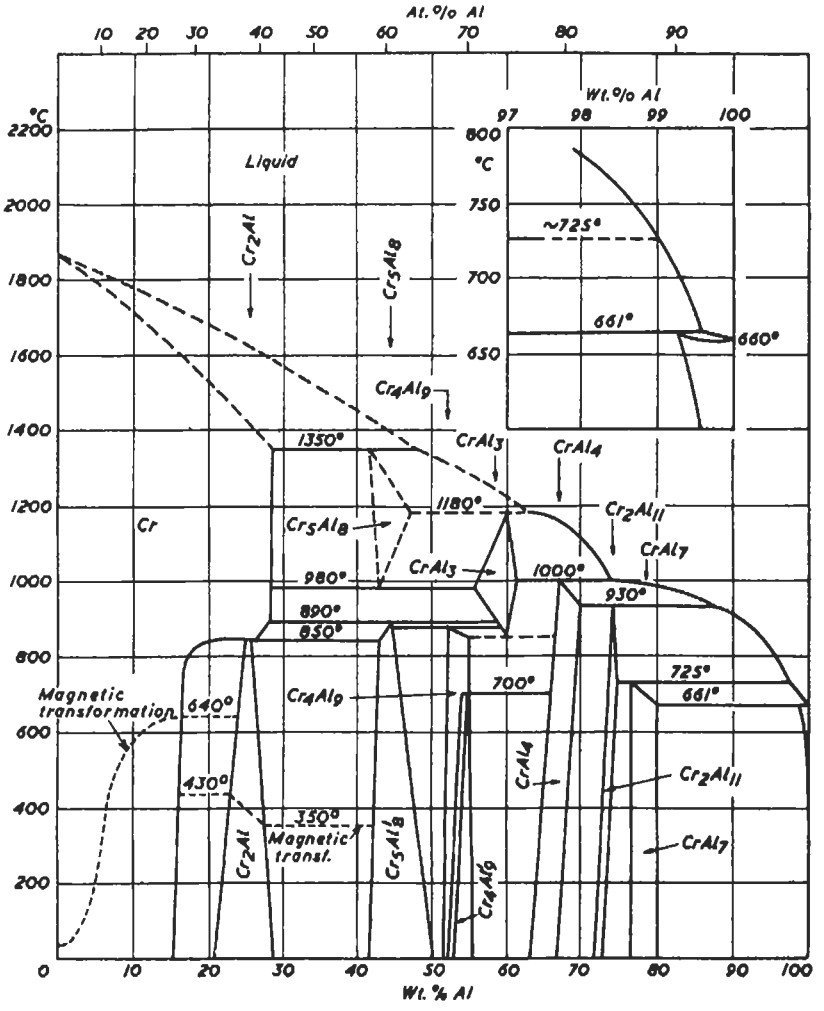
Al–Ce



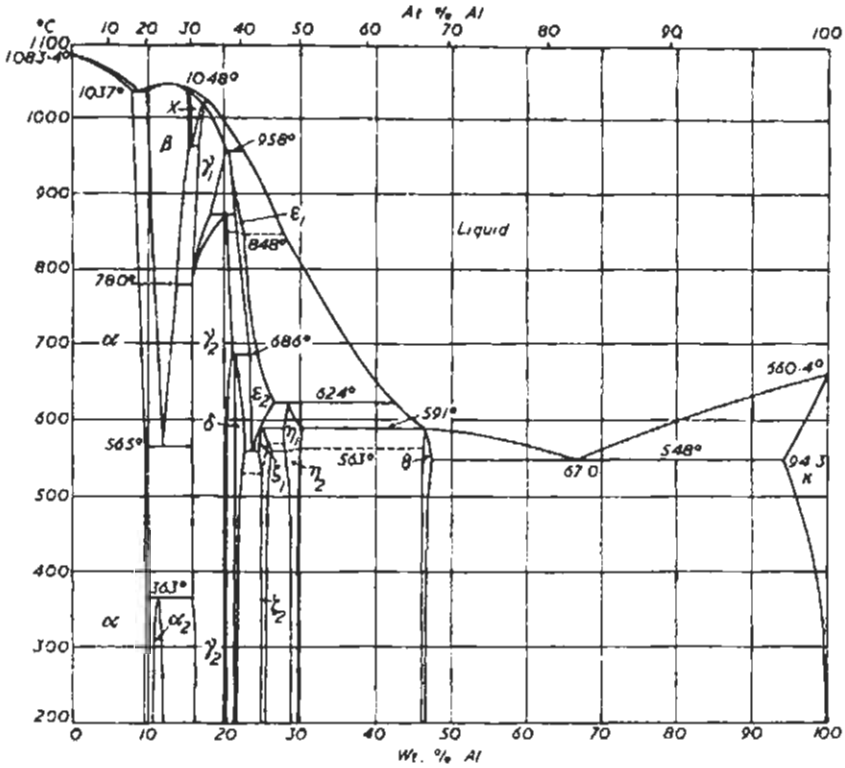
Al–Co


°C
At.% Al
Wt.% Al
Al Co
1628°
Al5Co2
Al9Co2
Al13Co4
Liquid
1495°
1400°
γ
βCo
1170°
1115°
943°
Magnetic transformation
840°
657°
660°
420°
βCo
αCo
γ

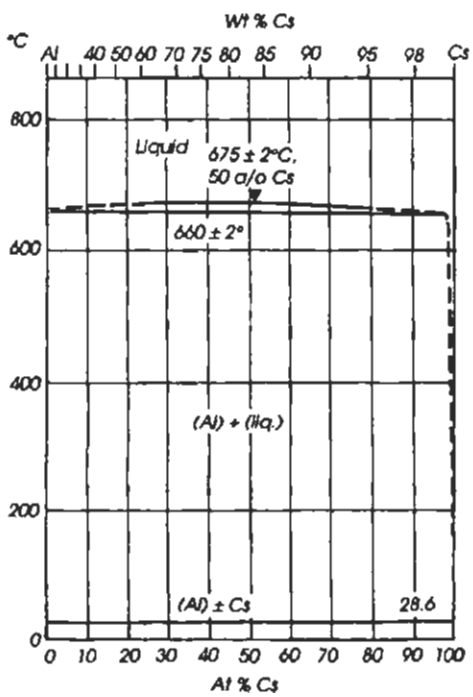
Al–Cr


At. % Al
10 20 30 40 50 60 70 80 90
°C
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Liquid
Cr
Cr2Al
Cr5Al8
Cr4Al9
CrAl3
CrAl4
Cr2Al11
CrAl7
1350°
1180°
980°
890°
850°
1000°
930°
700°
725°
661°
640°
430°
350°
Magnetic transformation
Magnetic transf.
10 20 30 40 50 60 70 80 90 100
Wt. % Al
Wt. % Al
97 98 99 100
800
750
700
650
°C
~725°
661°
660°

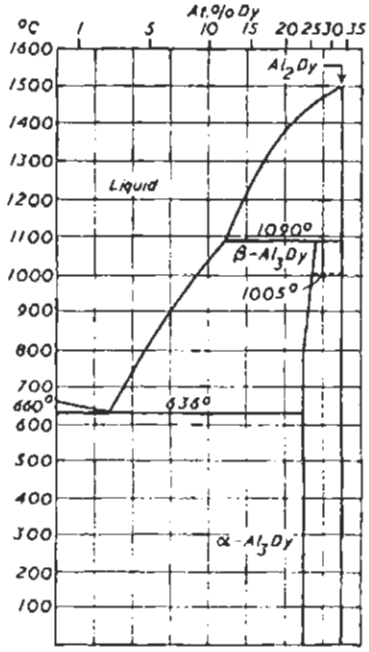
Al–Cu



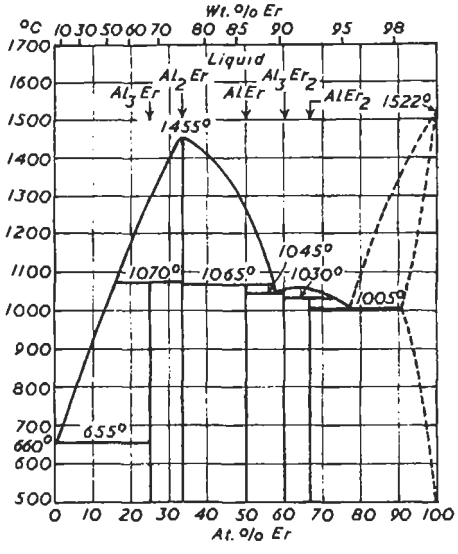
Al–Cs



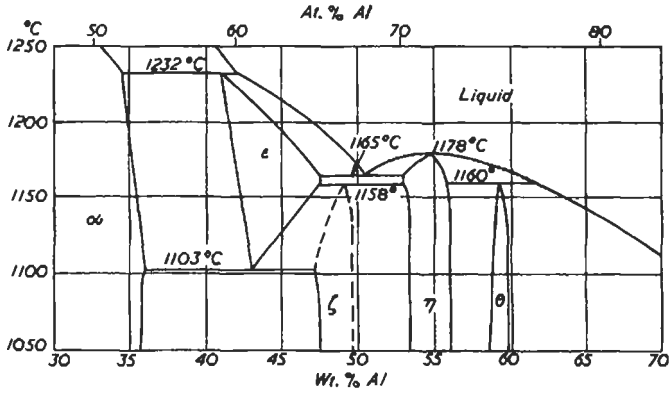
Al–Dy



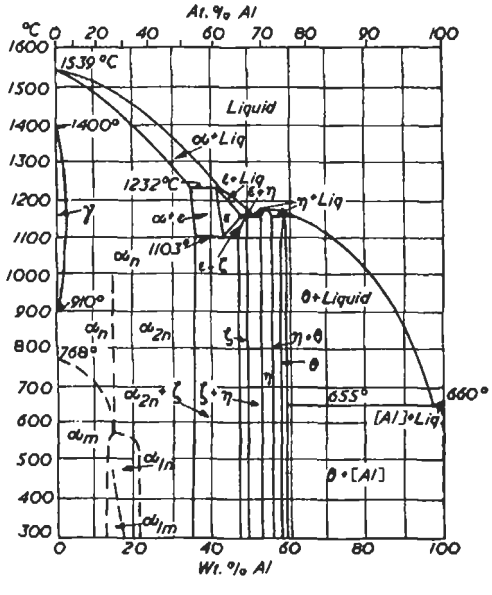
Al–Er



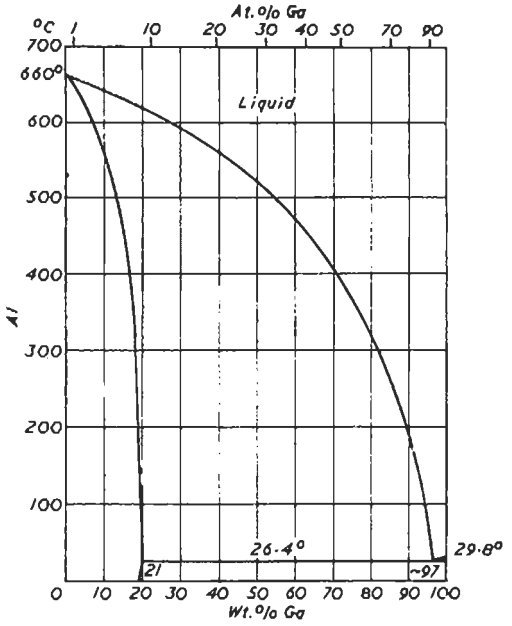
Al–Fe



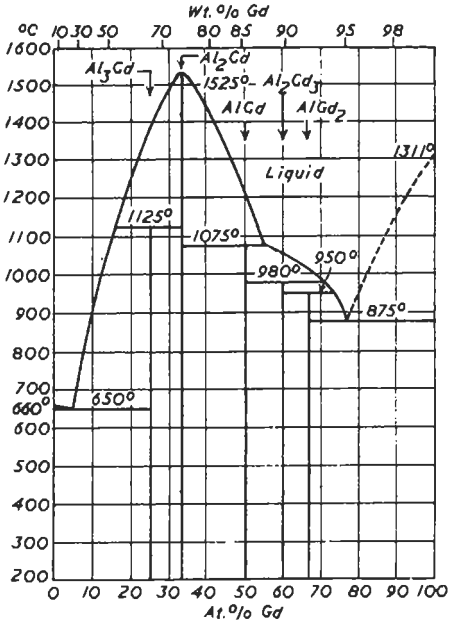
Al–Fe



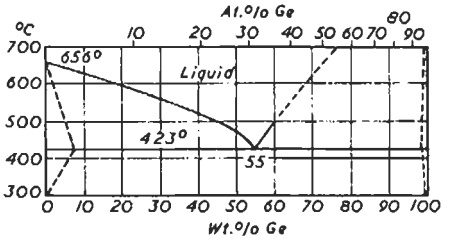
Al–Ga



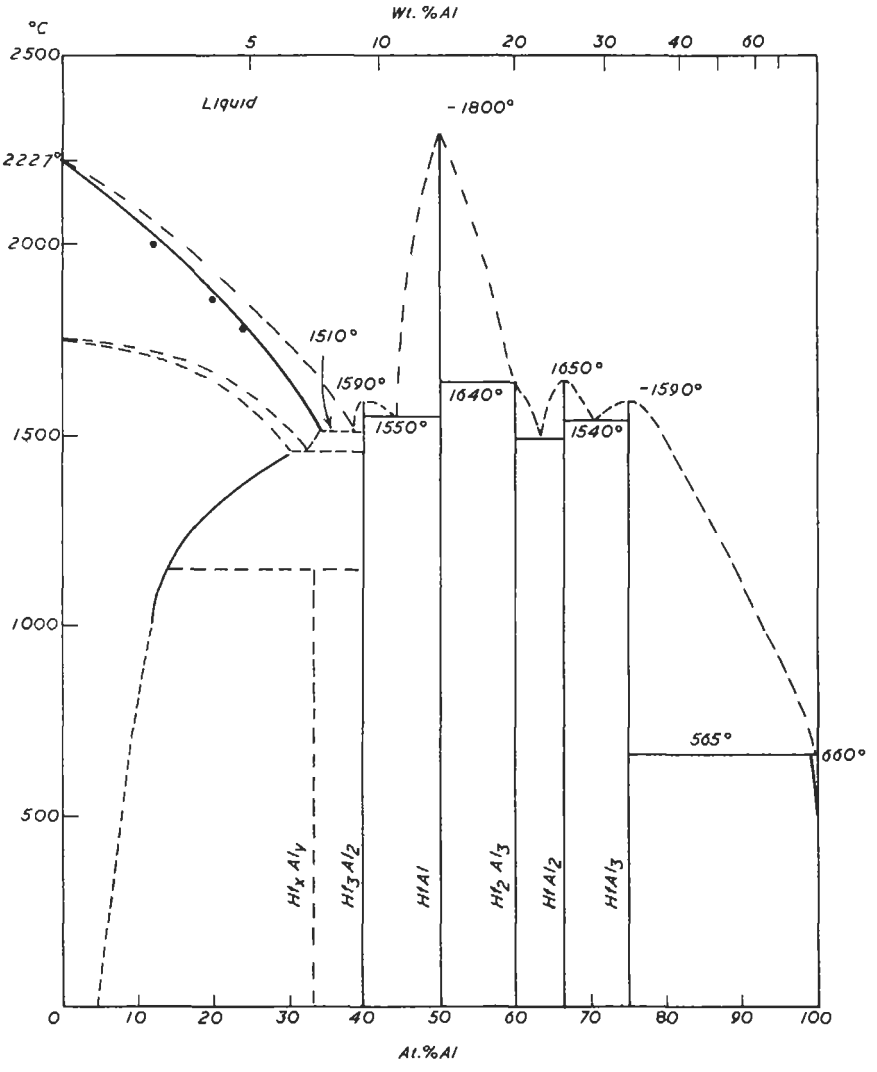
Al–Gd



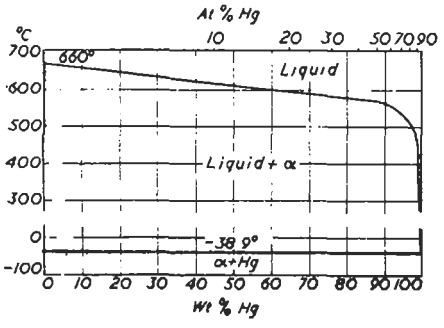
Al–Ge



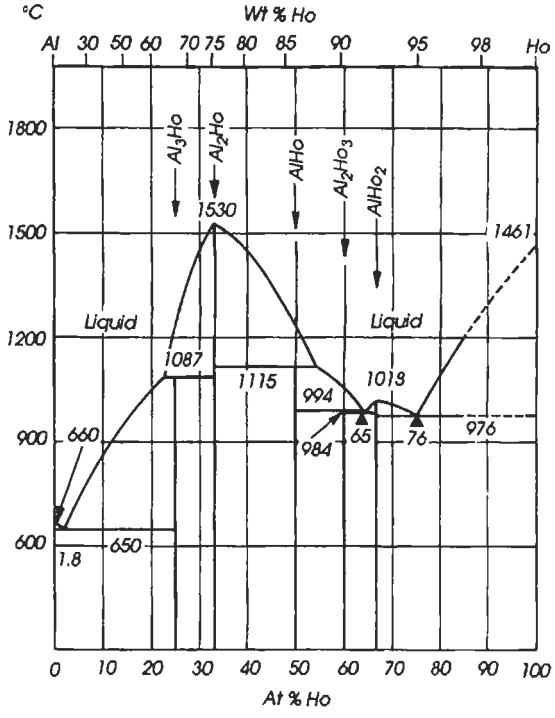
Al–Hf


°C
Wt. %Al
5
10
20
30
40
60
2500
2227°
2000
1500
1000
500
Liquid
~1800°
1510°
1590°
1550°
1640°
1650°
1540°
~1590°
565°
660°
Hf_xAl_y
Hf_3Al_2
HfAl
Hf_2Al_3
$HfAl_2$
$HfAl_3$
0
10
20
30
40
50
60
70
80
90
100
At.%Al

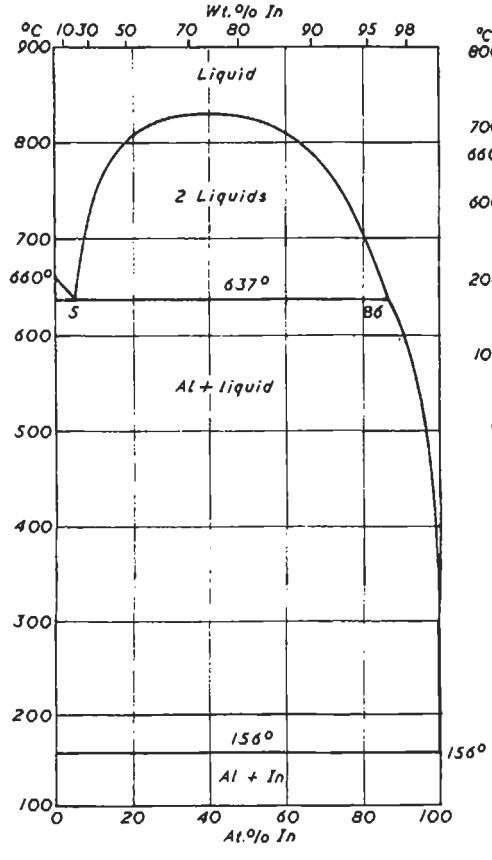
Al–Hg


At % Hg
°C
10
20
30
50
70
90
700
660°
600
500
400
300
Liquid
Liquid + α
0
-38.9°
-100
α+Hg
0
10
20
30
40
50
60
70
80
90
100
Wt % Hg

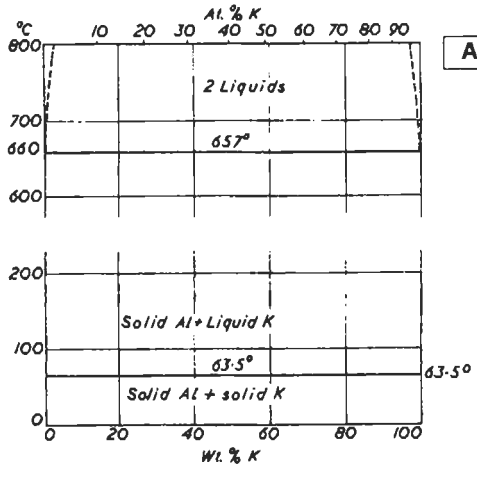
Al–Ho



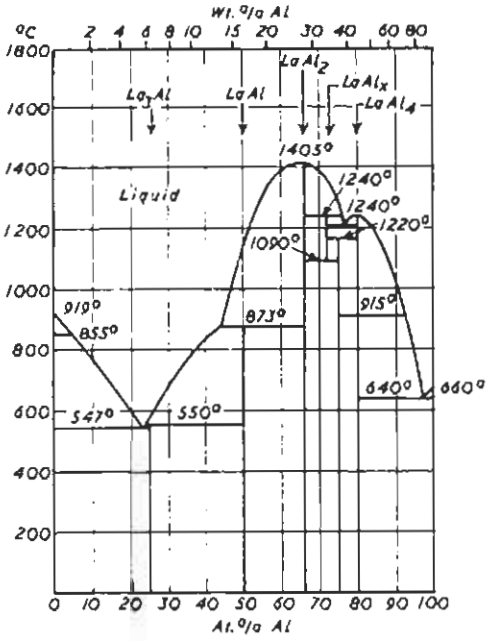
Al–In



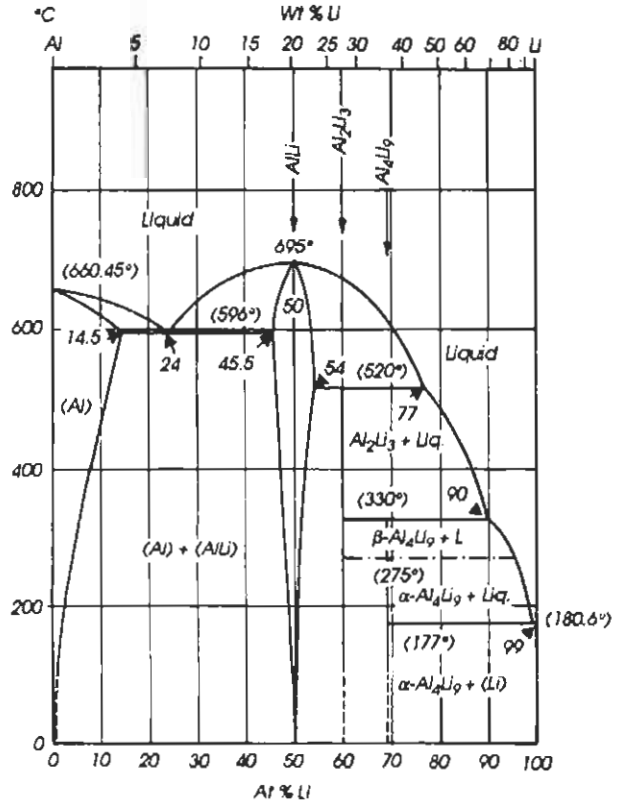
Al–K

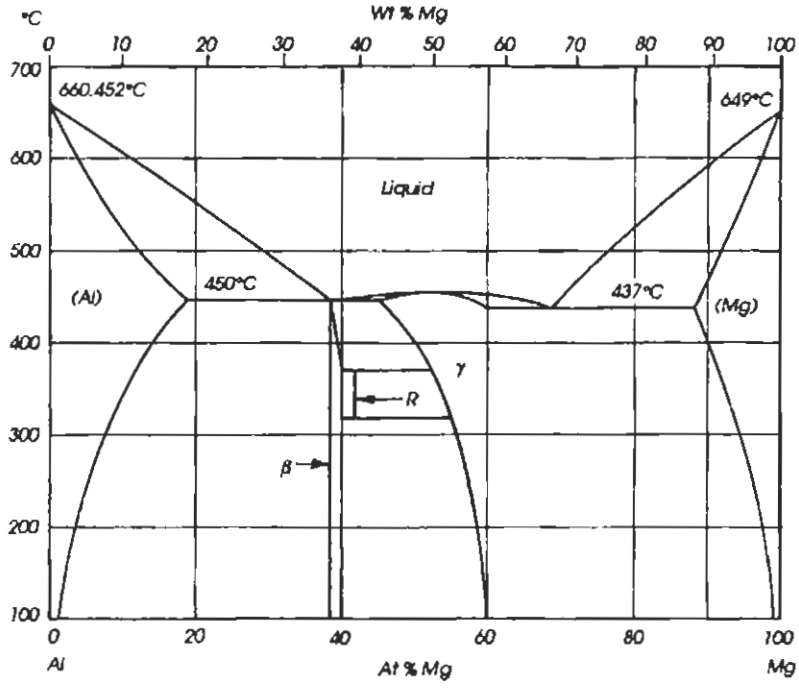


Al–La

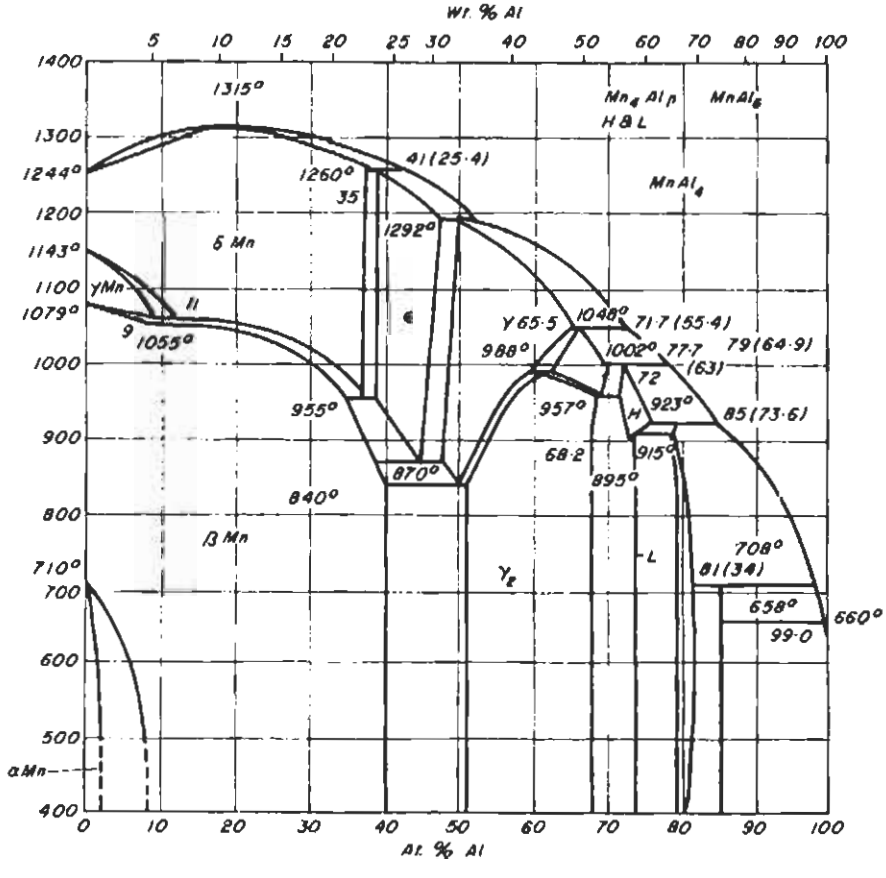

Wt. % Al
°C
2 4 6 8 10 15 20 30 40 60 80
1800
1600
1400
1200
1000
800
600
400
200
La_3Al
LaAl
$LaAl_2$
$LaAl_x$
$LaAl_4$
1405°
1240°
1240°
1220°
1090°
915°
873°
919°
855°
640°
660°
547°
550°
Liquid
0 10 20 30 40 50 60 70 80 90 100
At. % Al

Al–Li


°C
Wt % Li
Al 5 10 15 20 25 30 40 50 60 80 Li
800
600
400
200
0
AlLi
Al_2Li_3
Al_4Li_9
Liquid
695°
(660.45°)
(596°)
50
14.5
24
45.5
54
(520°)
77
Liquid
(Al)
Al_2Li_3 + Liq.
(330°)
90
β-Al_4Li_9 + L
(Al) + (AlLi)
(275°)
α-Al_4Li_9 + Liq.
(180.6°)
(177°)
99
α-Al_4Li_9 + (Li)
0 10 20 30 40 50 60 70 80 90 100
At % Li

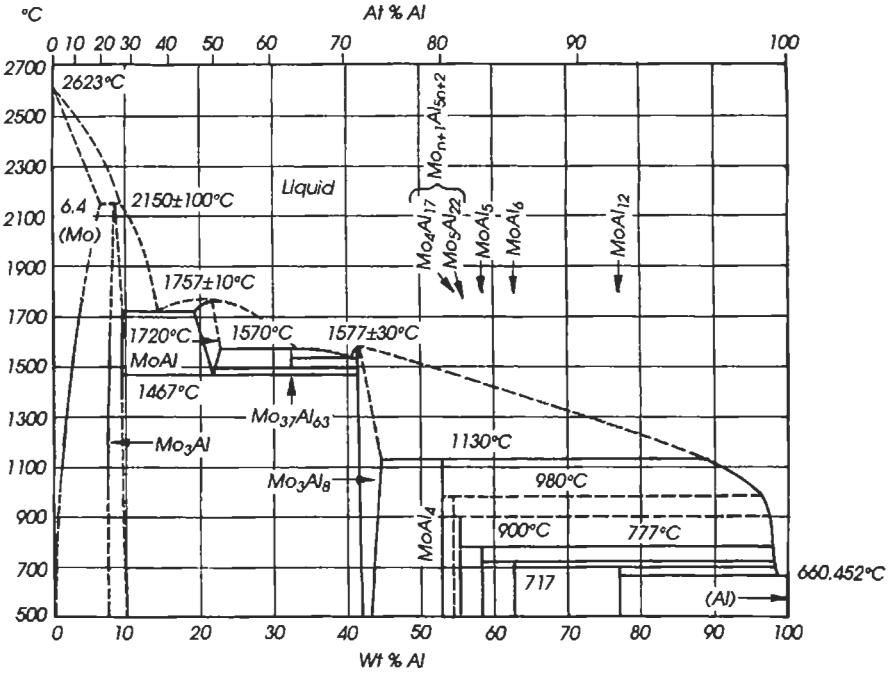

°C
Wt % Mg
0 10 20 30 40 50 60 70 80 90 100
700 600 500 400 300 200 100
660.452°C
649°C
Liquid
(Al)
450°C
437°C
(Mg)
γ
R
β
0 20 40 60 80 100
Al
At % Mg
Mg

Al–Mg

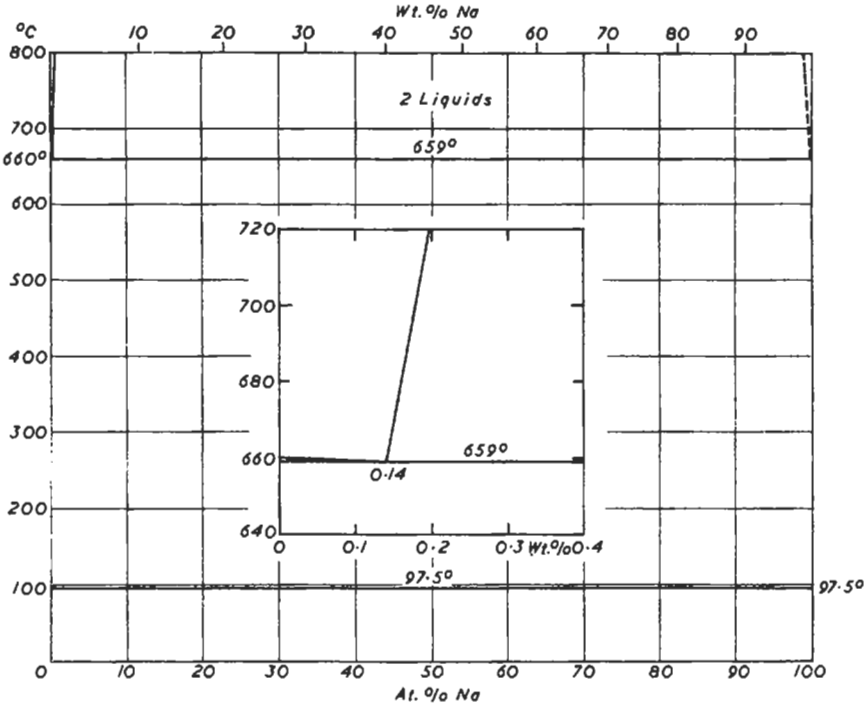

Wt. % Al
5 10 15 20 25 30 40 50 60 70 80 90 100
1400 1300 1244° 1200 1143° 1100 1079° 1000 900 800 710° 700 600 500 400
1315°
Mn4 Al11
H & L
MnAl6
41(25·4)
1260°
35
MnAl4
1292°
δ Mn
γMn
11
9
1055°
ε
Y 65·5
1048°
71·7(55·4)
988°
1002°
77·7
79(64·9)
(63)
72
955°
957°
H
923°
85(73·6)
68·2
915°
895°
870°
840°
β Mn
L
708°
81(34)
658°
660°
99·0
Yε
αMn
0 10 20 30 40 50 60 70 80 90 100
At. % Al

Al–Mn

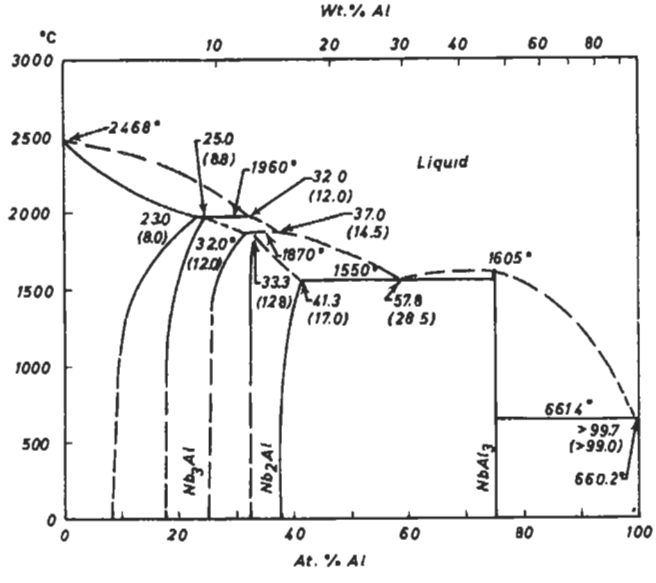
Al–Mo


°C
At % Al
0 10 20 30 40 50 60 70 80 90 100
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
2623°C
Liquid
6.4
(Mo)
2150±100°C
1757±10°C
1720°C
1570°C
1577±30°C
MoAl
1467°C
Mo37Al63
Mo3Al
Mo3Al8
1130°C
980°C
900°C
777°C
717
660.452°C
(Al)
MoAl4
Mo4Al17
Mon+1Al5n+2
Mo5Al22
MoAl5
MoAl6
MoAl12
0 10 20 30 40 50 60 70 80 90 100
Wt % Al

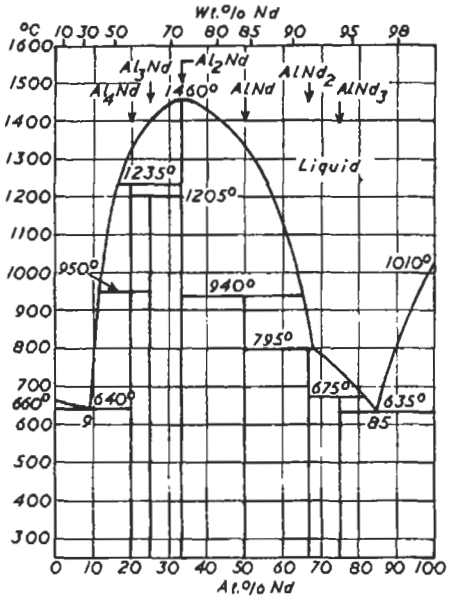
Al–Na


Wt. % Na
°C
2 Liquids
659°
660°
720
700
680
660
640
0·14
0·1
0·2
0·3 Wt.%
0·4
97·5°
At. % Na

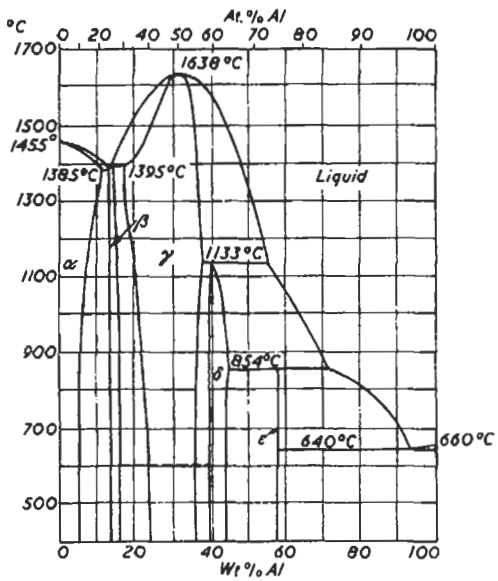
Al–Nb


Wt.% Al
°C
2468°
25.0
(8.8)
1960°
32 0
(12.0)
Liquid
37.0
(14.5)
23.0
(8.0)
32.0°
(12.0)
1870°
1550°
1605°
33.3
(12.8)
41.3
(17.0)
57.8
(28 5)
6614°
> 99.7
(>99.0)
660.2°
Nb3Al
Nb2Al
NbAl3
At. % Al

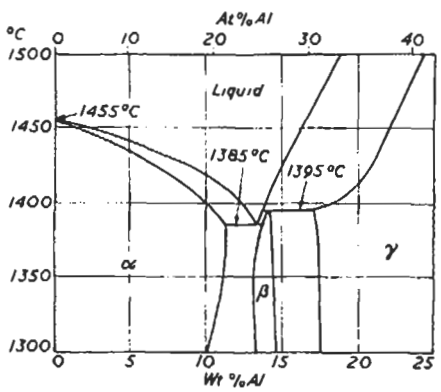
Al–Nd



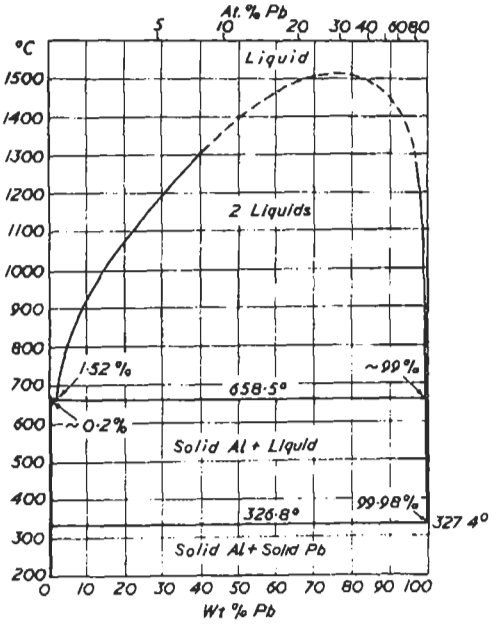
Al–Ni



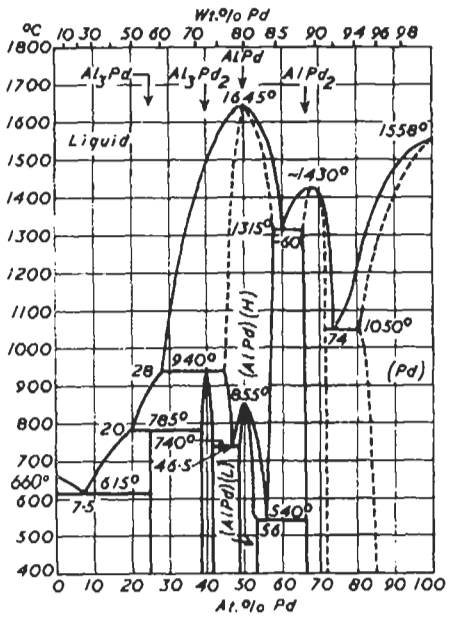
Al–Ni



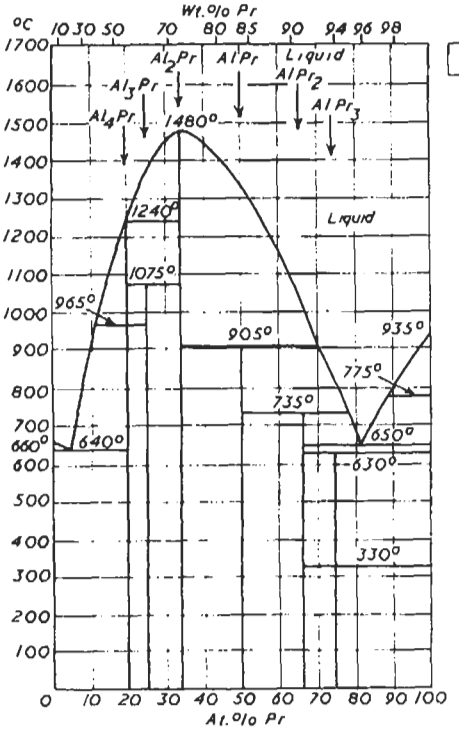
Al–Pb



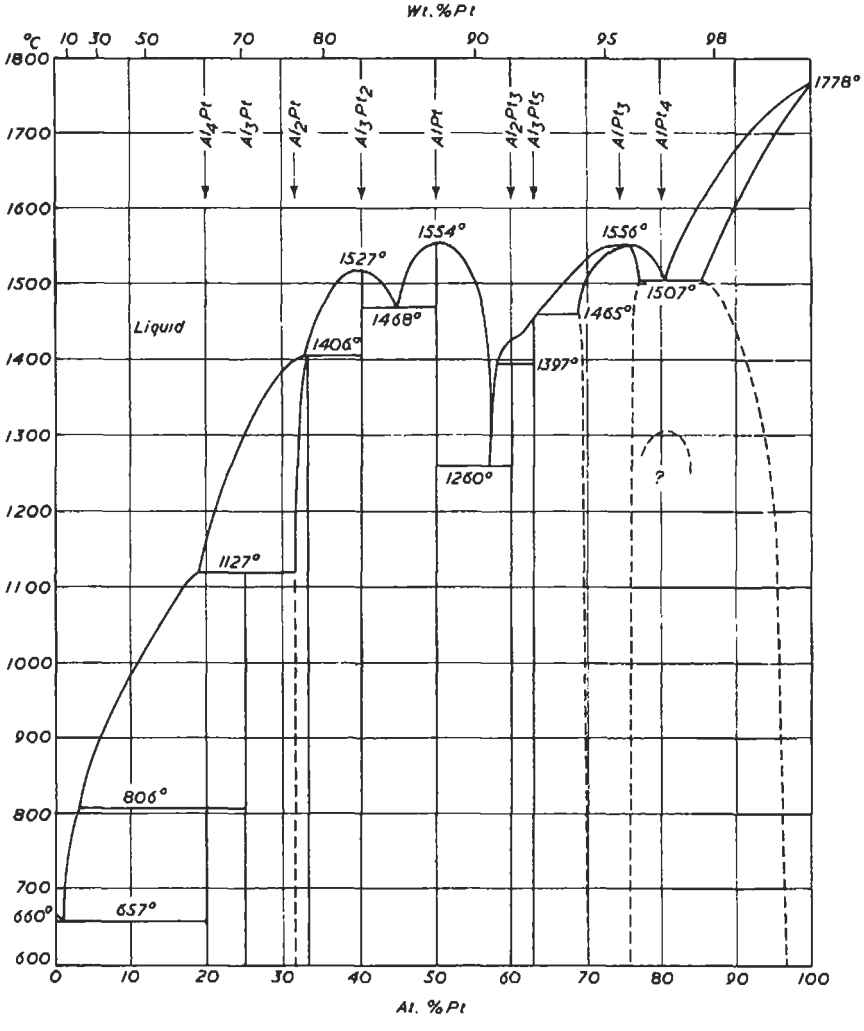
Al–Pd



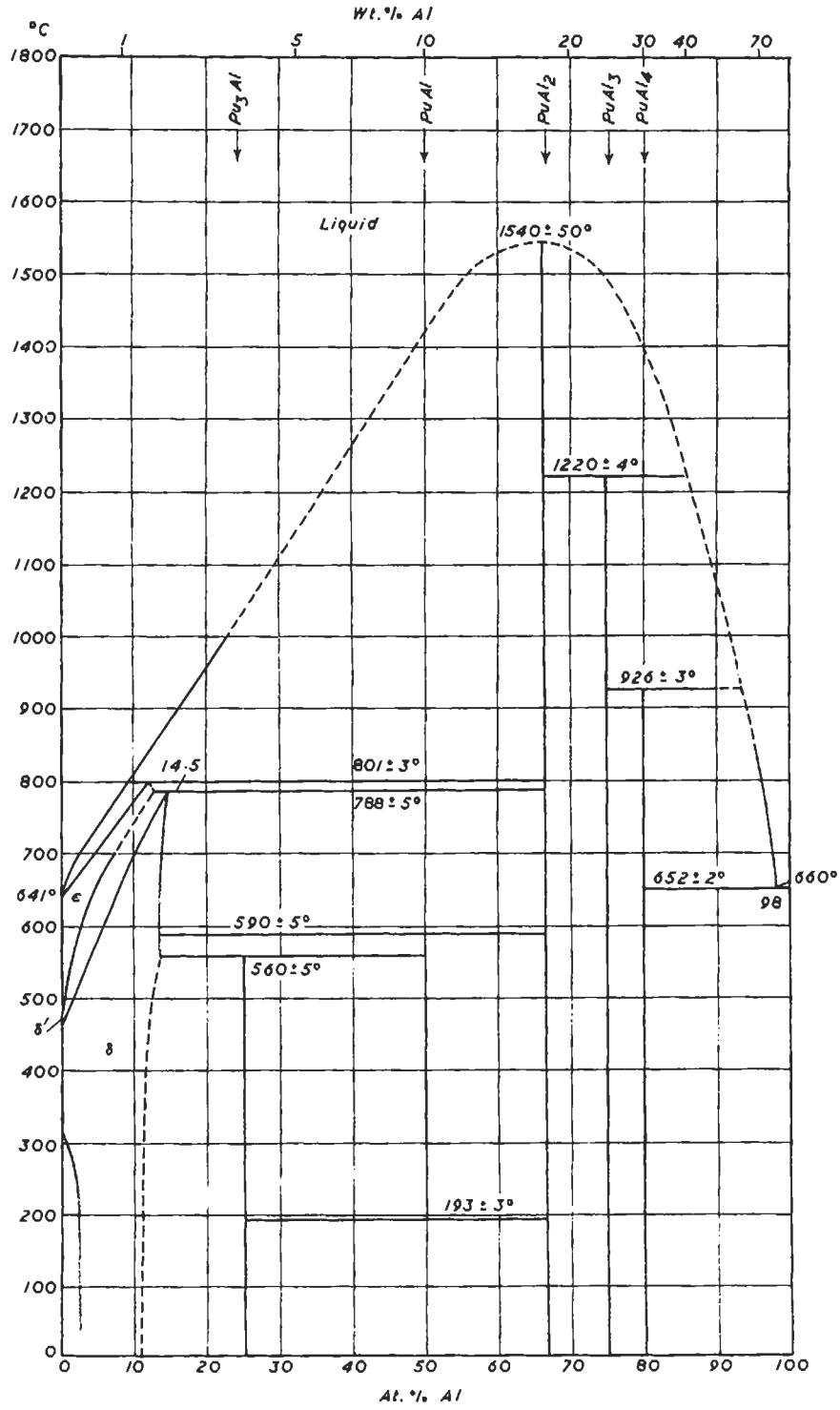
Al–Pr



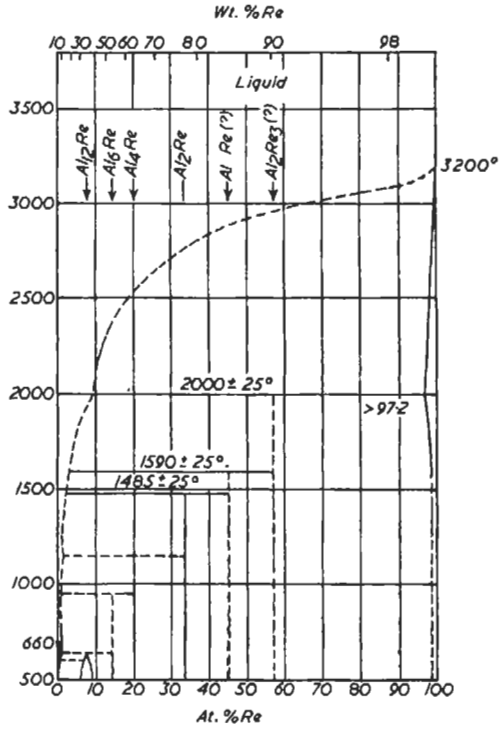
Al–Pt


Wt. % Pt
°C
10 30 50 70 80 90 95 98
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
660°
600
Al4Pt
Al3Pt
Al2Pt
Al3Pt2
AlPt
Al2Pt3
Al3Pt5
AlPt3
AlPt4
1778°
1554°
1556°
1527°
1507°
1468°
1465°
1406°
1397°
1260°
1127°
806°
657°
Liquid
?
0 10 20 30 40 50 60 70 80 90 100
At. % Pt

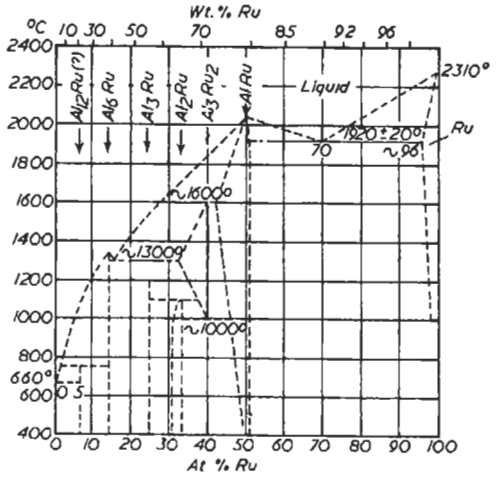
Al–Pu


°C
Wt. % Al
1
5
10
20
30
40
70
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
641°
600
500
400
300
200
100
0
Pu3Al
PuAl
PuAl2
PuAl3
PuAl4
Liquid
1540 ± 50°
1220 ± 4°
926 ± 3°
14.5
801 ± 3°
788 ± 5°
652 ± 2°
660°
98
590 ± 5°
560 ± 5°
193 ± 3°
ε
δ'
δ
0
10
20
30
40
50
60
70
80
90
100
At. % Al

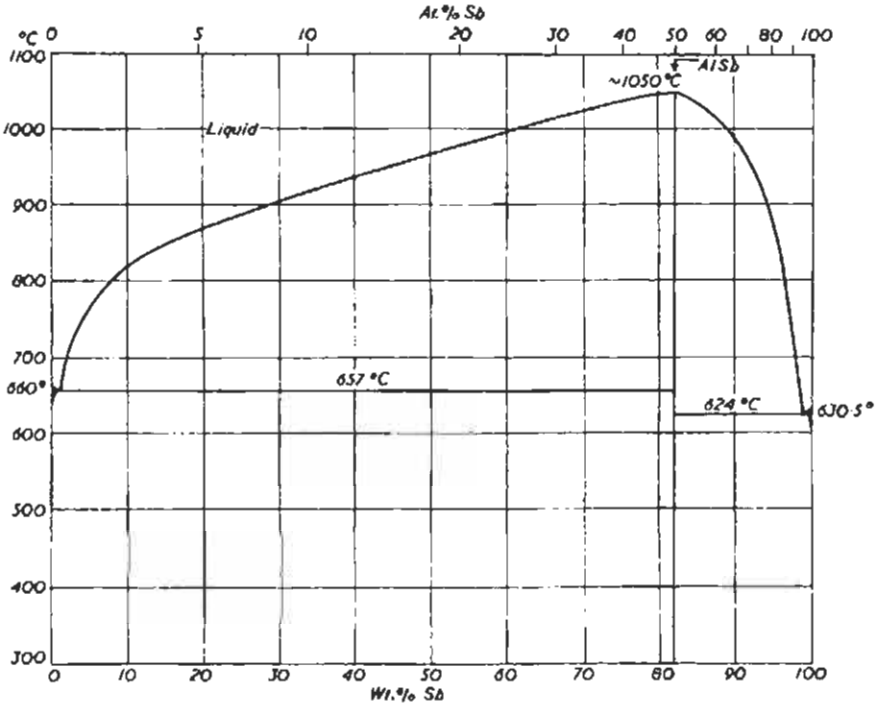
Al–Re


Wt. % Re
10 30 50 60 70 80 90 98
Liquid
Al12Re
Al6Re
Al4Re
Al2Re
Al Re (?)
Al2Re3 (?)
3200°
2000 ± 25°
>97·2
1590 ± 25°.
1485 ± 25°
3500
3000
2500
2000
1500
1000
660
500
0 10 20 30 40 50 60 70 80 90 100
At. % Re

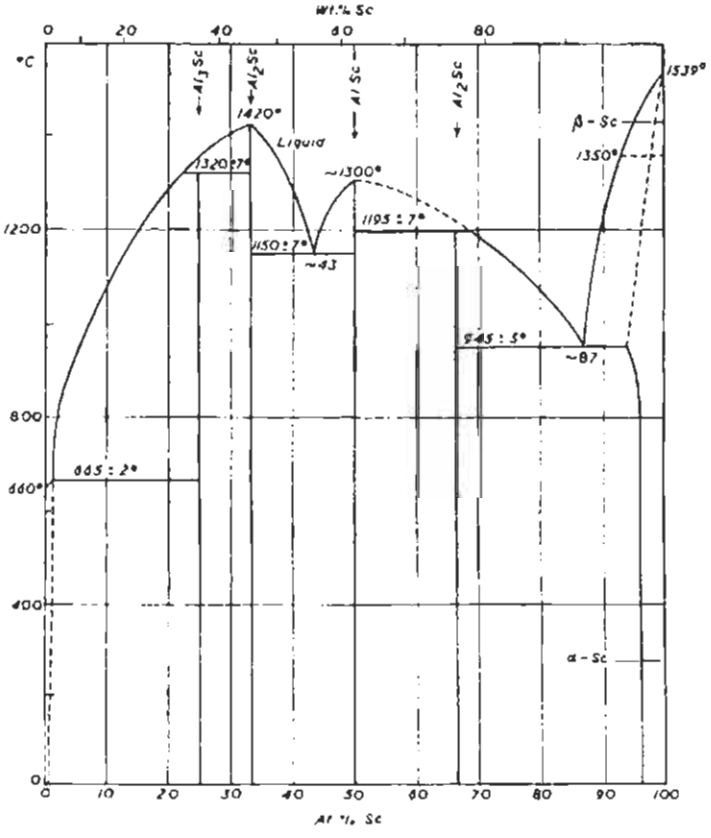
Al–Ru


Wt. % Ru
°C 10 30 50 70 85 92 96
Al12Ru (?)
Al6Ru
Al3Ru
Al2Ru
Al3Ru2
Al Ru
Liquid
2310°
1620 ± 20°
70
~98
Ru
~1600°
~1300°
~1000°
2400
2200
2000
1800
1600
1400
1200
1000
800
660°
600
400
0 10 20 30 40 50 60 70 80 90 100
At % Ru

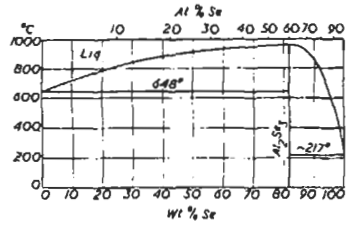
Al–Sb


At.% Sb
°C
Liquid
~1050°C
AlSb
657 °C
624 °C
630·5°
Wt.% Sb

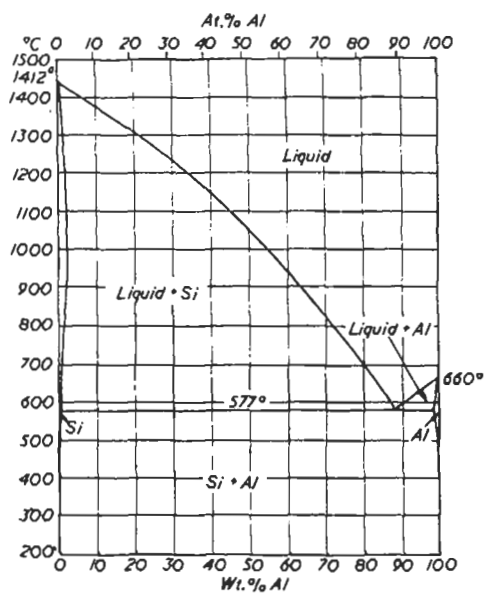
Al–Sc


Wt.% Sc
°C
Al3Sc
Al2Sc
Al Sc
Al2Sc
1420°
Liquid
1320 ± 7°
~1300°
1195 ± 7°
1150 ± 7°
~43
645 ± 5°
~87
1539°
β - Sc
1350°
665 ± 2°
α - Sc
At % Sc

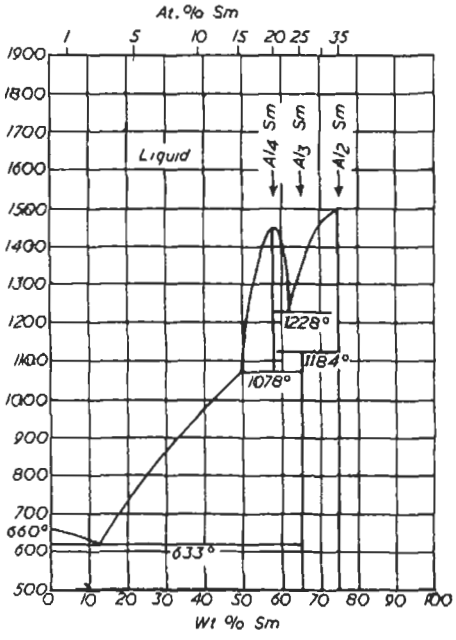
Al–Se



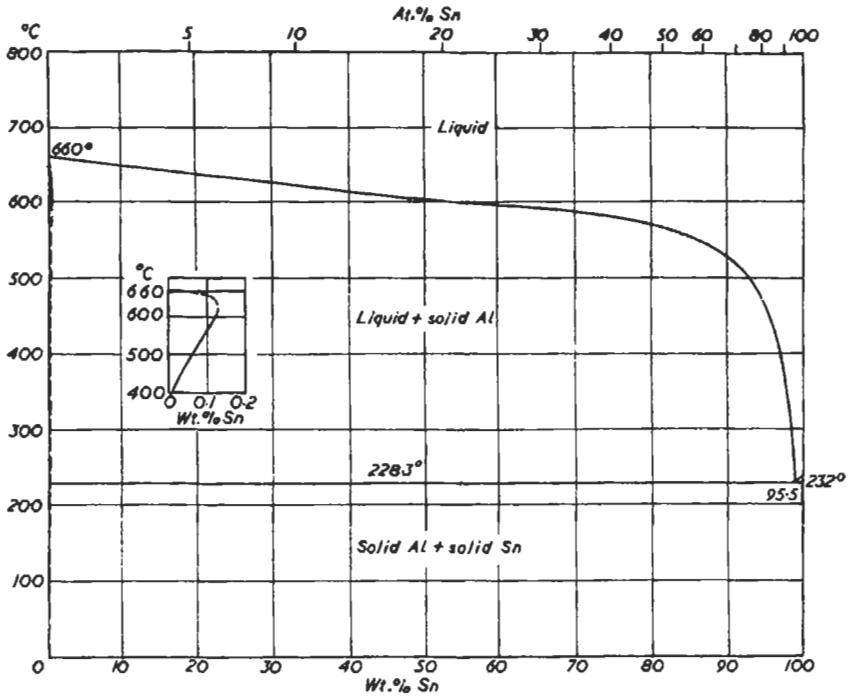
Al–Si



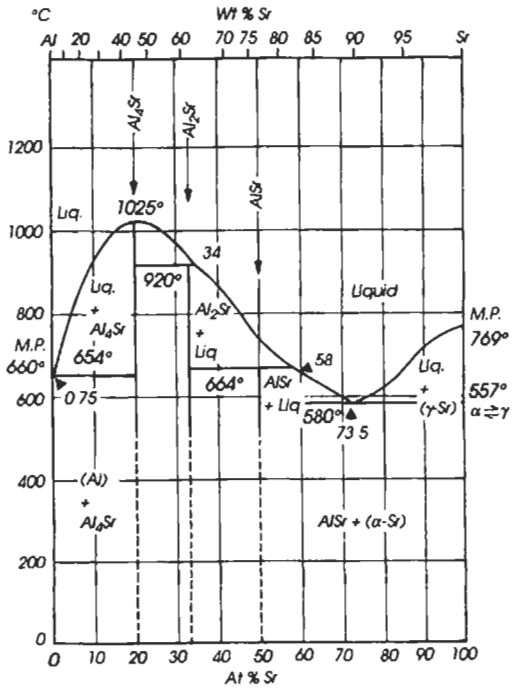
Al–Sm



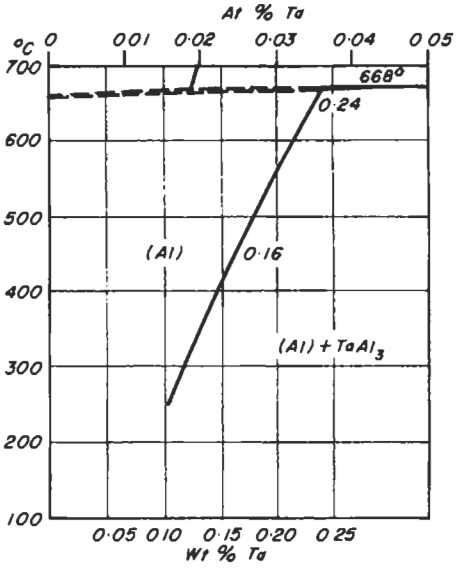
Al–Sn


°C
At.% Sn
5
10
20
30
40
50
60
80
100
800
700
600
500
400
300
200
100
0
660°
Liquid
Liquid + solid Al
2283°
232°
95·5
Solid Al + solid Sn
10
20
30
40
50
60
70
80
90
100
Wt.% Sn
°C
660
600
500
400
0
0·1
0·2
Wt.% Sn

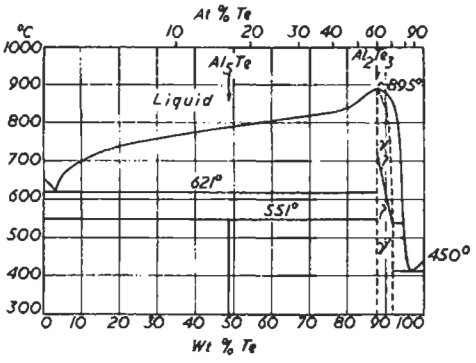
Al–Sr


°C
Wt % Sr
Al
20
40
50
60
70
75
80
85
90
95
Sr
Al_4Sr
Al_2Sr
AlSr
1200
1000
800
600
400
200
0
Liq.
1025°
34
920°
Liq.
+
Al_4Sr
654°
0·75
Al_2Sr
+
Liq
664°
AlSr
+ Liq
58
580°
73·5
Liquid
M.P.
769°
Liq.
+
(γ-Sr)
557°
α ⇌ γ
M.P.
660°
(Al)
+
Al_4Sr
AlSr + (α-Sr)
10
20
30
40
50
60
70
80
90
100
At % Sr

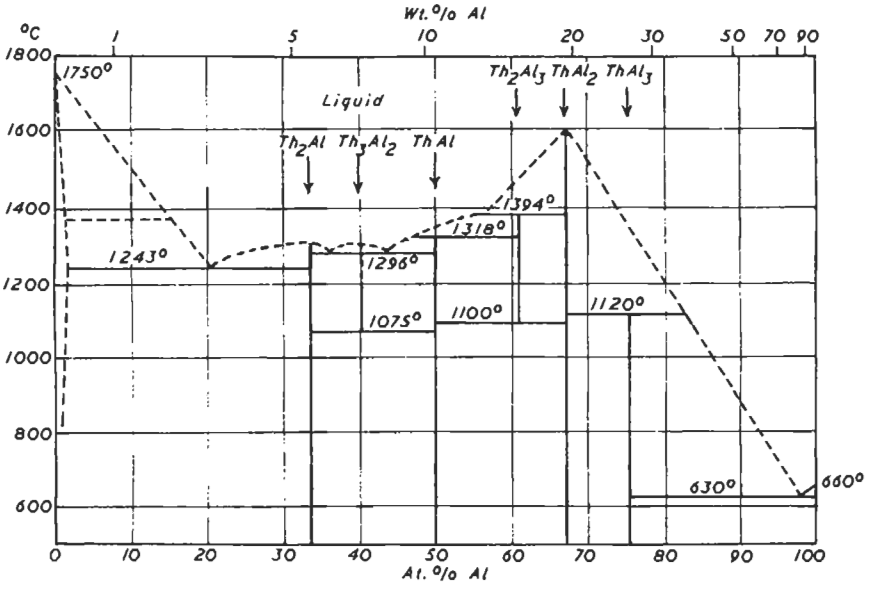
Al–Ta



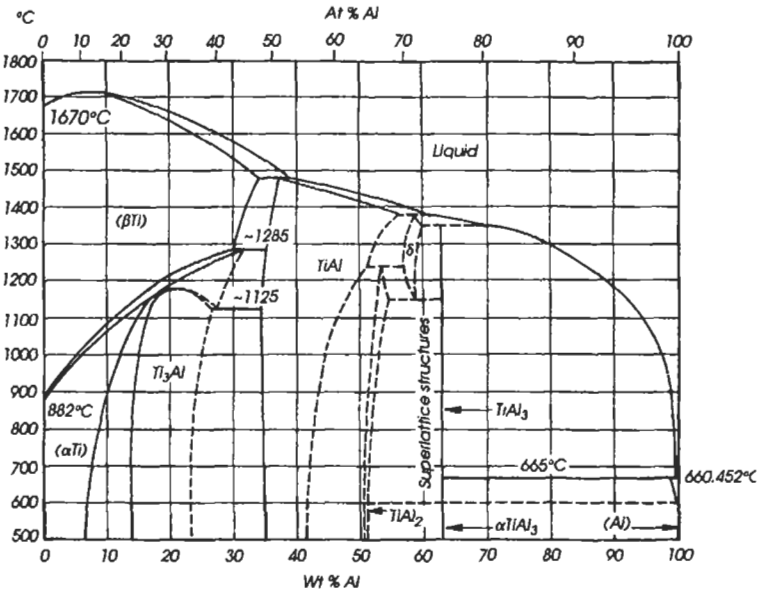
Al–Te



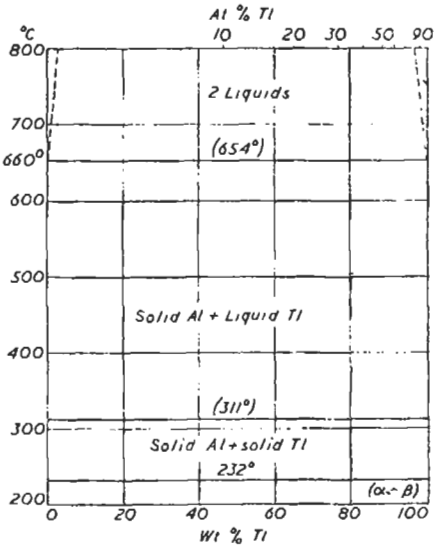
Al–Th



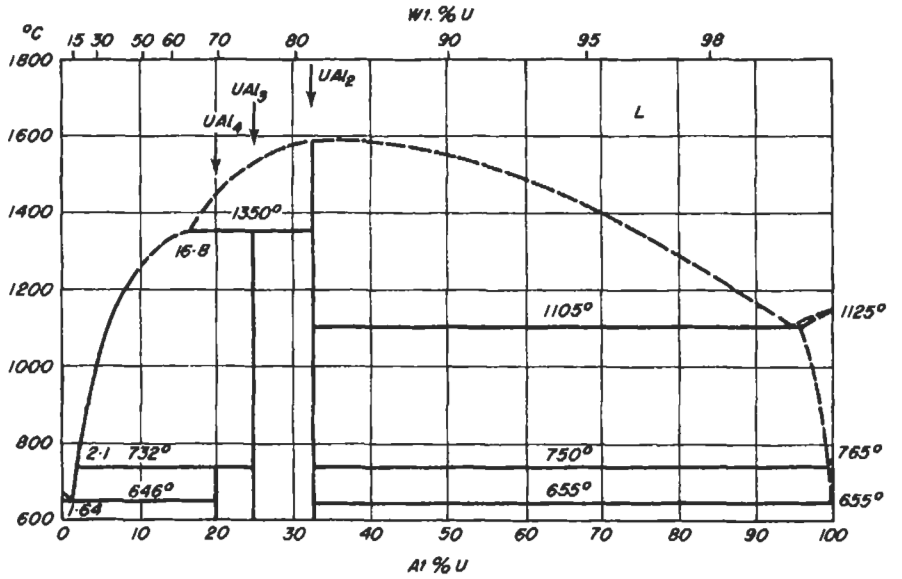
Al–Ti


°C
At % Al
1670°C
Liquid
(βTi)
~1285
~1125
TiAl
δ?
Ti3Al
882°C
(αTi)
Superlattice structures
TiAl3
665°C
660.452°C
TiAl2
αTiAl3
(Al)
Wt % Al

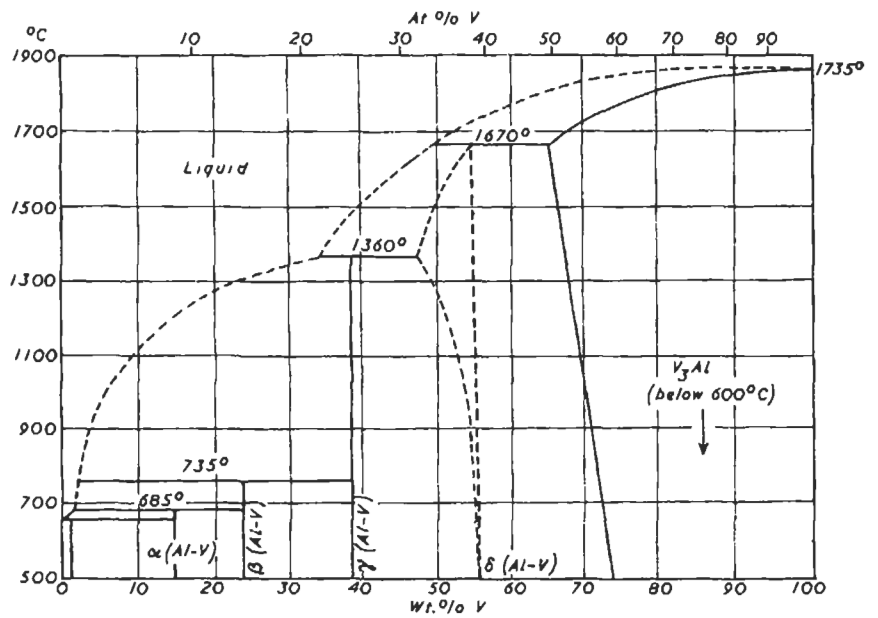
Al–Tl


At % Tl
°C
2 Liquids
(654°)
660°
Solid Al + Liquid Tl
(311°)
Solid Al + solid Tl
232°
(α + β)
Wt % Tl

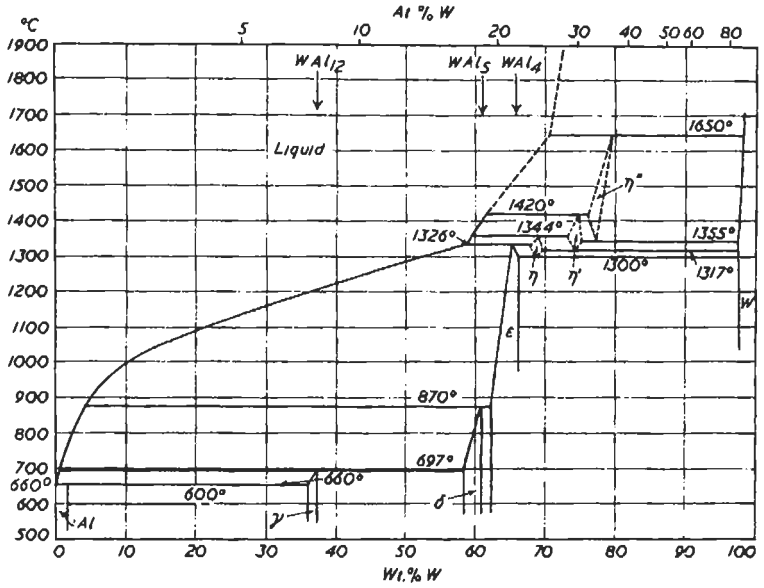
Al–U


Wt. % U
°C
15 30 50 60 70 80 90 95 98
1800
1600
1400
1200
1000
800
600
UAl3
UAl2
UAl4
L
1350°
16·8
1105°
1125°
2·1 732°
750°
765°
646°
655°
655°
1·64
0 10 20 30 40 50 60 70 80 90 100
At % U

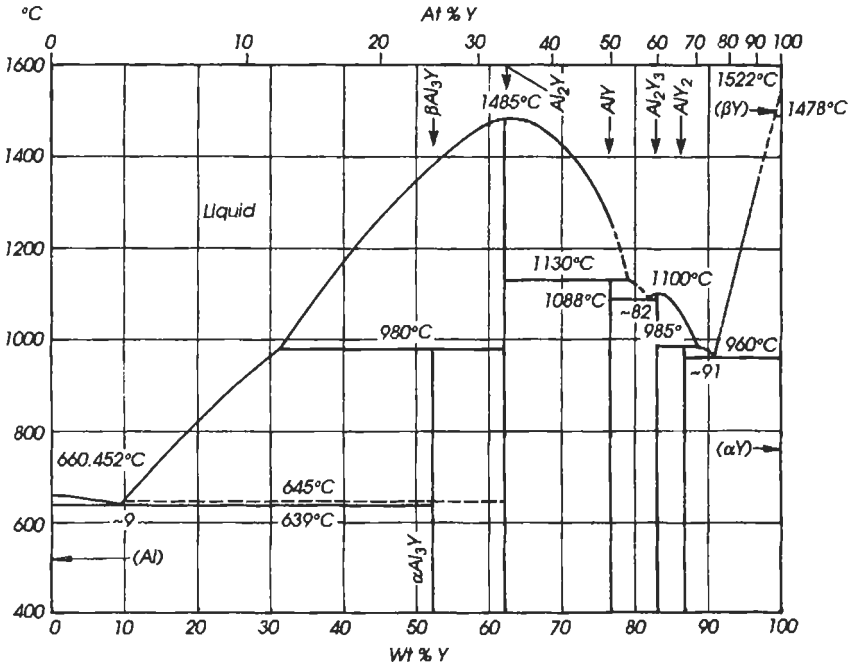
Al–V


At °/o V
°C
10 20 30 40 50 60 70 80 90
1900
1700
1500
1300
1100
900
700
500
1735°
1670°
Liquid
1360°
V3Al
(below 600°C)
735°
685°
α (Al-V)
β (Al-V)
γ (Al-V)
δ (Al-V)
0 10 20 30 40 50 60 70 80 90 100
Wt.°/o V

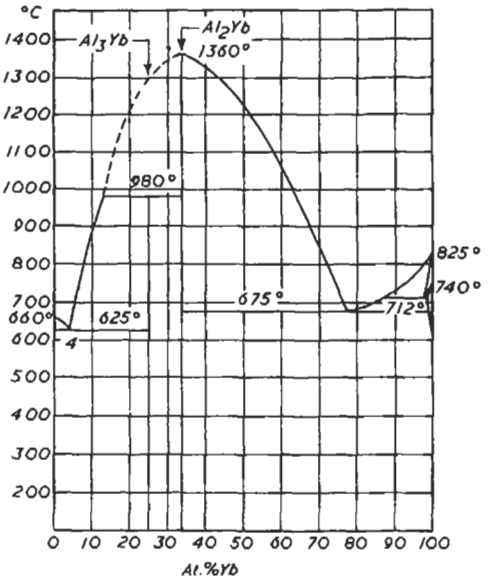
Al–W


°C
At % W
WAl12
WAl5
WAl4
Liquid
1650°
1420°
1344°
1326°
1355°
1300°
1317°
η"
η
η'
ε
870°
697°
660°
660°
600°
δ
γ
Al
W
Wt.% W

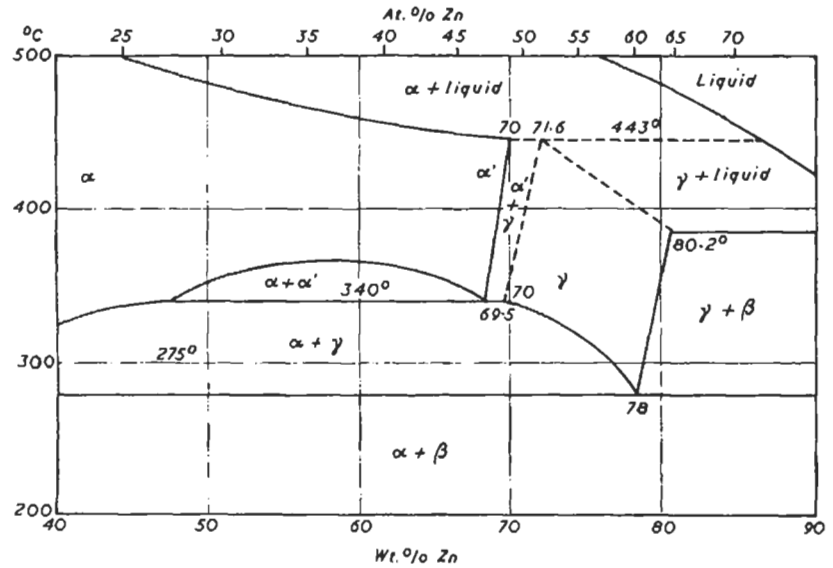
Al–Y


°C
At % Y
βAl3Y
1485°C
Al2Y
AlY
Al2Y3
AlY2
1522°C
(βY)
1478°C
Liquid
1130°C
1100°C
1088°C
~82
985°
960°C
~91
980°C
660.452°C
645°C
~9
639°C
(Al)
αAl3Y
(αY)
Wt % Y

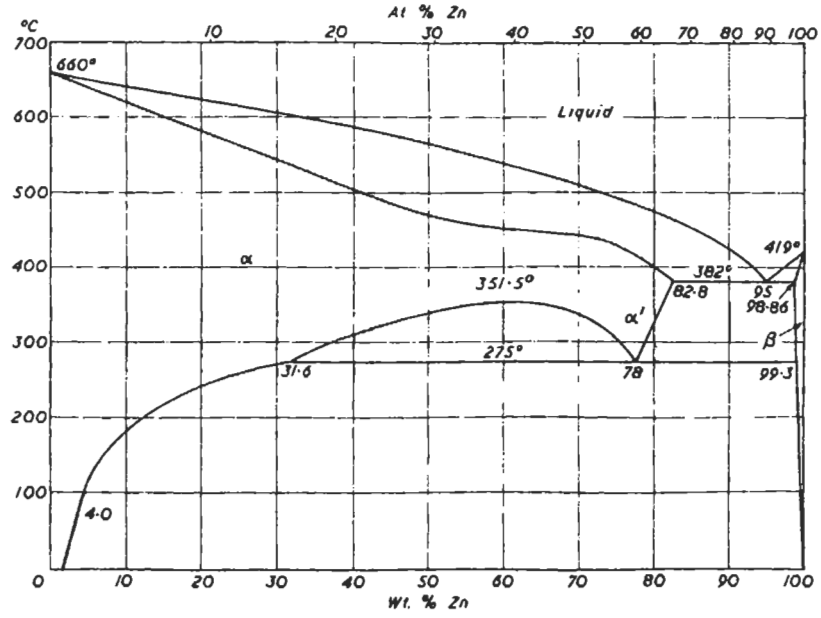
Al–Yb


°C
1400
1300
1200
1100
1000
900
800
700
660°
600
500
400
300
200
Al_3Yb
Al_2Yb
1360°
980°
825°
740°
675°
712°
625°
4
0 10 20 30 40 50 60 70 80 90 100
At.%Yb

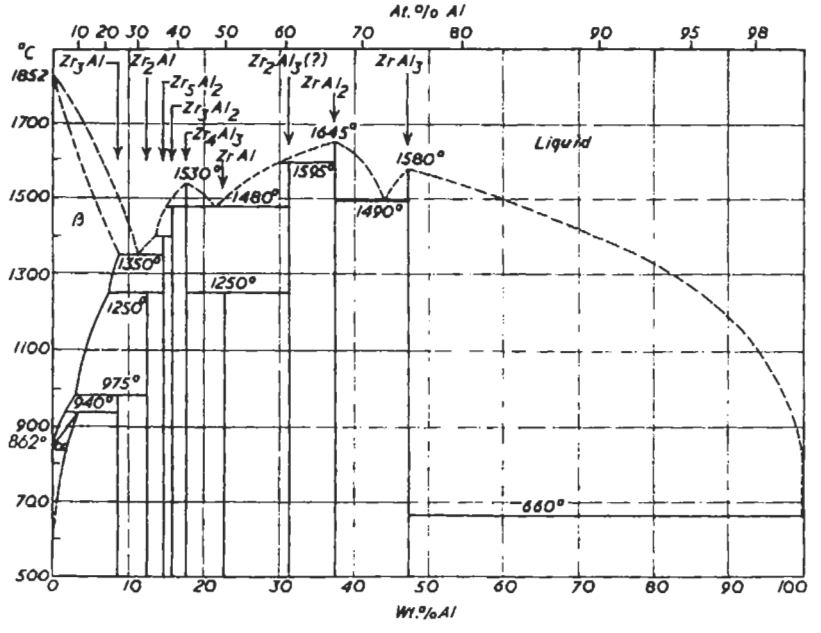
Al–Zn


At.% Zn
°C
25 30 35 40 45 50 55 60 65 70
500
400
300
200
α + liquid
Liquid
70 71.6 443°
α
α'
α' + γ
γ + liquid
80·2°
α+α' 340°
γ
70
69·5
γ + β
275°
α + γ
78
α + β
40 50 60 70 80 90
Wt.% Zn

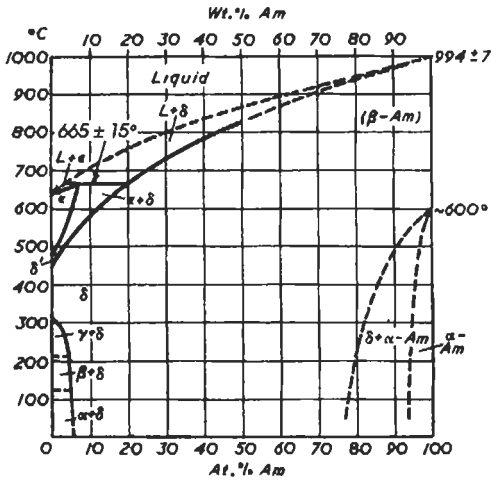
Al–Zn


At % Zn
°C
660°
Liquid
α
419°
382°
351·5°
82·8
95
98·86
α'
β
275°
31·6
78
99·3
4·0
Wt. % Zn

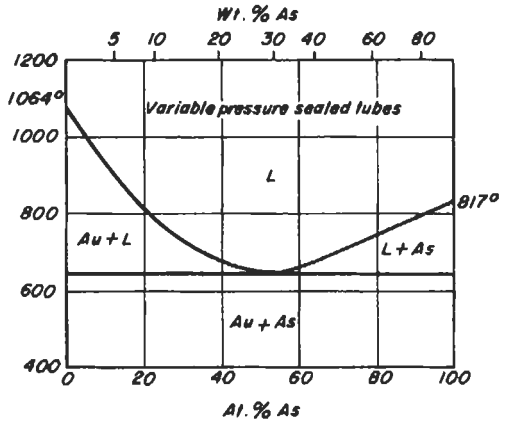
Al–Zr


At. % Al
°C
Zr3Al
Zr2Al
Zr5Al2
Zr3Al2
Zr4Al3
ZrAl
Zr2Al3(?)
ZrAl2
ZrAl3
1852
1645°
1580°
Liquid
1530°
1595°
1480°
1490°
β
1350°
1250°
1250°
975°
940°
862°
α
660°
Wt.% Al

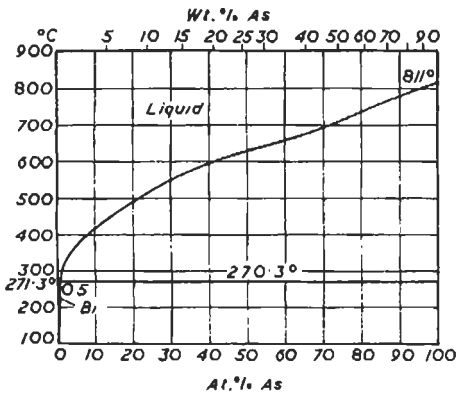
Am–Pu



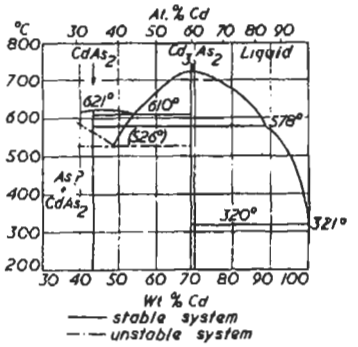
As–Au



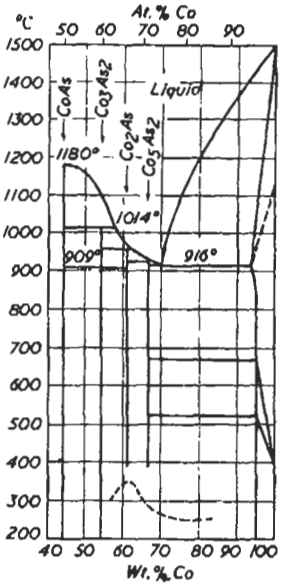
As–Bi



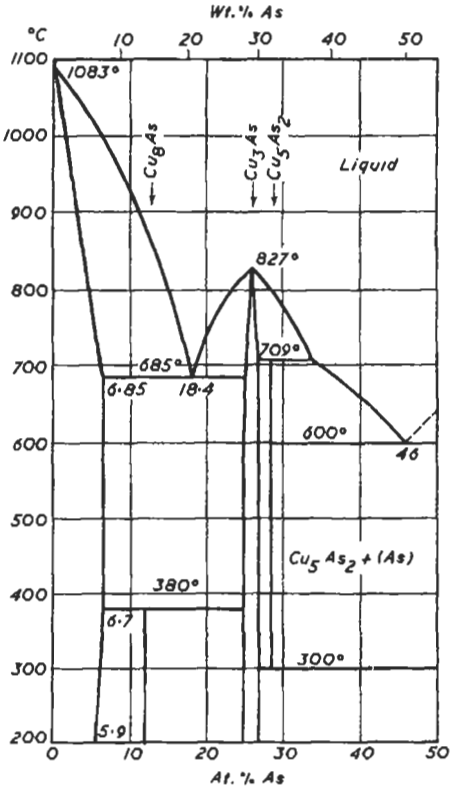
As–Cd



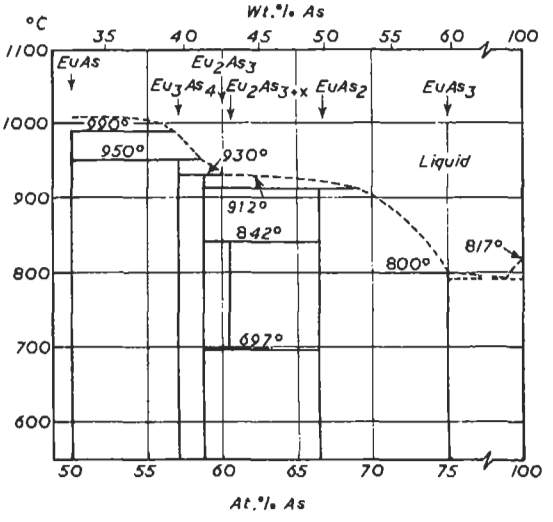
As–Co



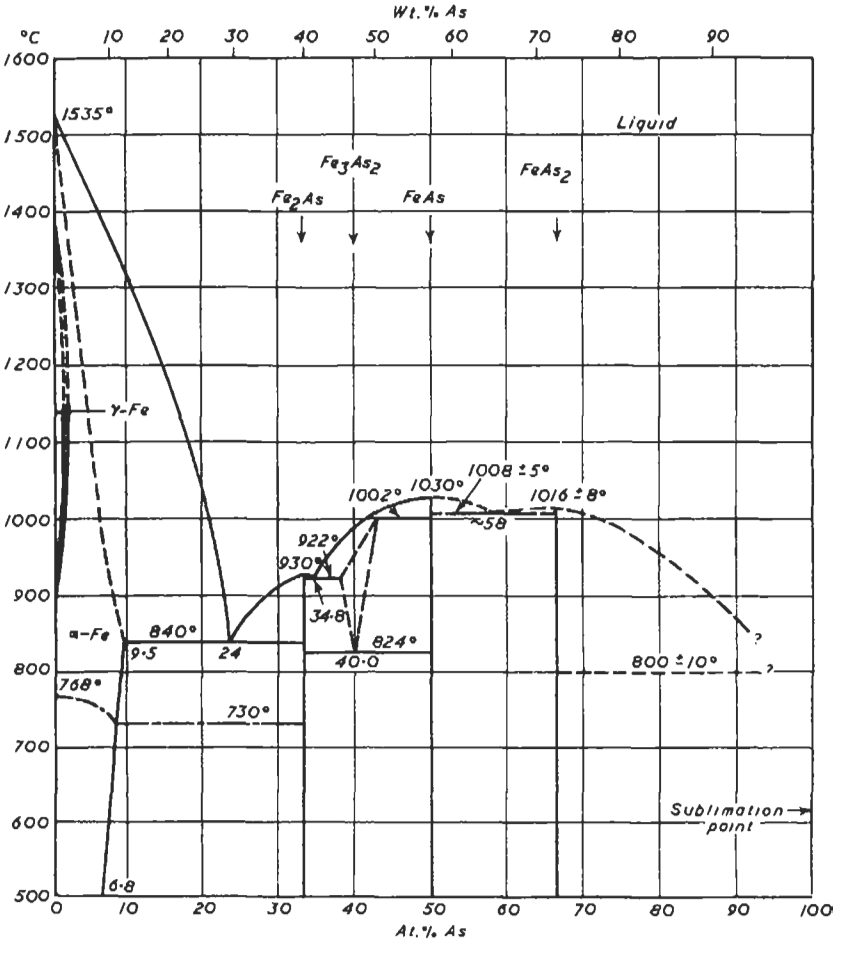
As–Cu



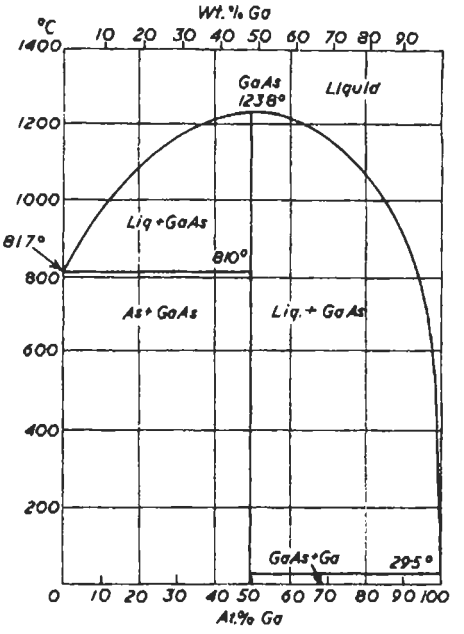
As–Eu


Wt.% As
°C
35 40 45 50 55 60 100
1100
1000
900
800
700
600
EuAs
Eu2As3
Eu3As4
Eu2As3+x
EuAs2
EuAs3
950°
930°
Liquid
912°
842°
817°
800°
697°
50 55 60 65 70 75 100
At.% As

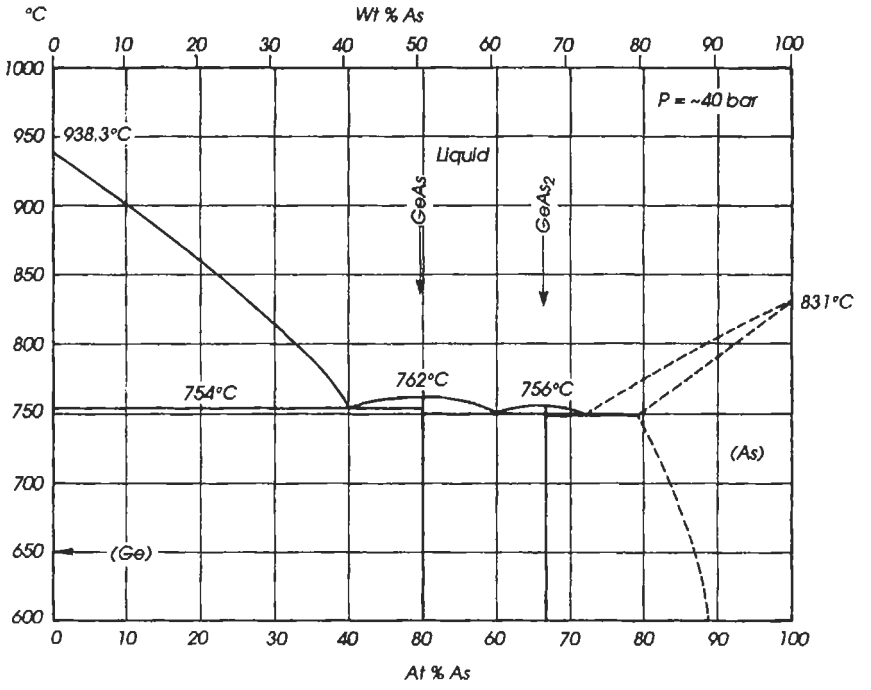
As–Fe


Wt.% As
°C
10 20 30 40 50 60 70 80 90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
1535°
Liquid
Fe3As2
Fe2As
FeAs
FeAs2
γ-Fe
1002°
1030°
1008 ± 5°
1016 ± 8°
~58
922°
930°
34·8
α-Fe
840°
9·5
24
824°
40·0
800 ± 10°
768°
730°
Sublimation point
6·8
0 10 20 30 40 50 60 70 80 90 100
At.% As

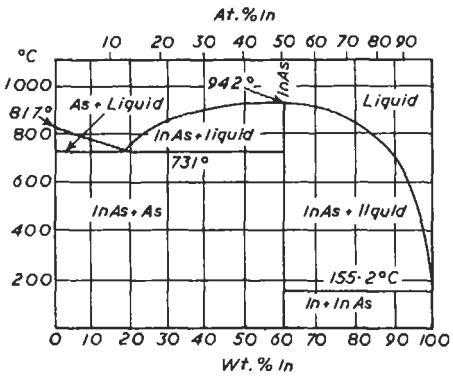
As-Ga


°C
Wt. % Ga
1400
1200
1000
800
600
400
200
10 20 30 40 50 60 70 80 90
GaAs
1238°
Liquid
Liq + GaAs
817°
810°
As + GaAs
Liq. + GaAs
GaAs + Ga
29.5°
0 10 20 30 40 50 60 70 80 90 100
At.% Ga

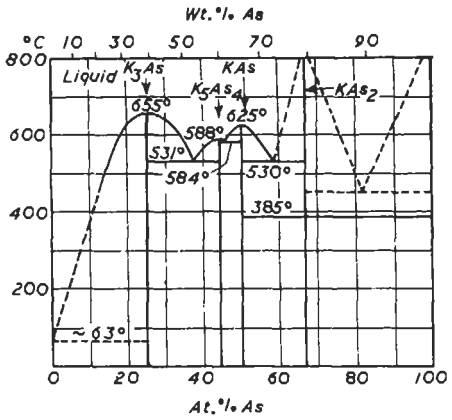
As–Ge


°C
Wt % As
1000
950
900
850
800
750
700
650
600
0 10 20 30 40 50 60 70 80 90 100
P = ~40 bar
938.3°C
Liquid
GeAs
GeAs2
831°C
754°C
762°C
756°C
(As)
(Ge)
At % As

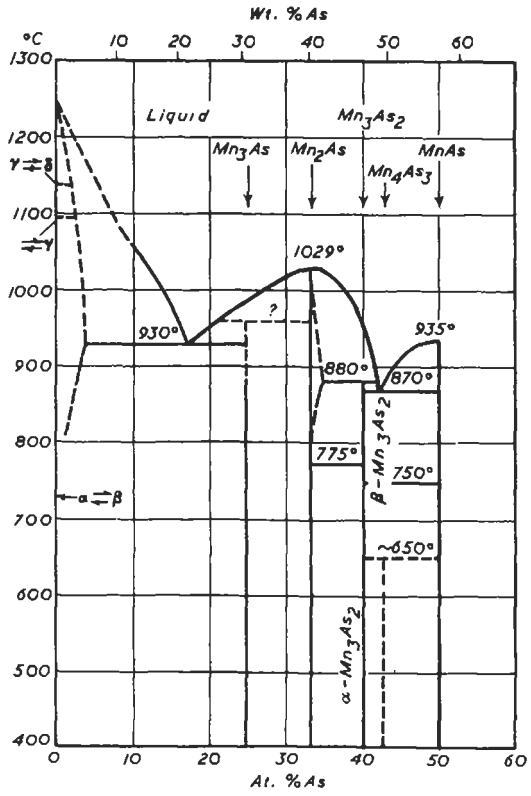
As–In



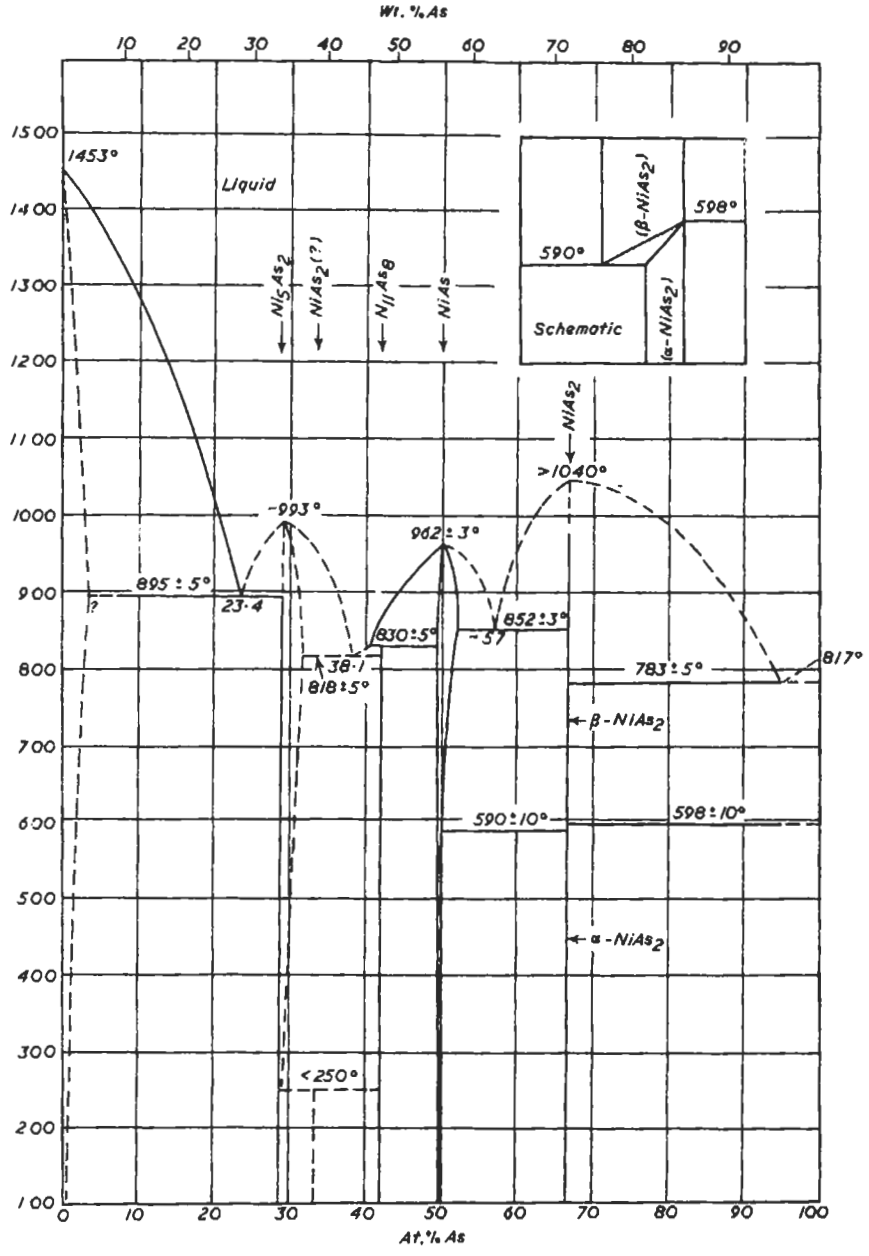
As–K



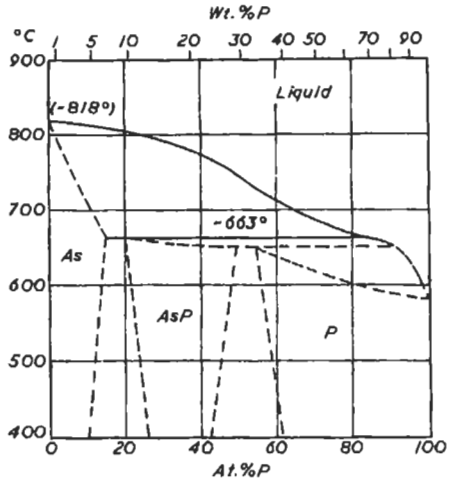
As–Mn



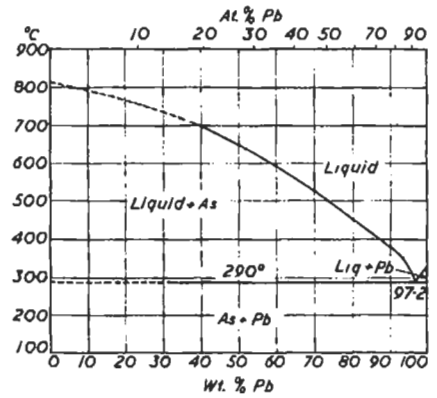
As–Ni


Wt. % As
10 20 30 40 50 60 70 80 90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0 10 20 30 40 50 60 70 80 90 100
At. % As
1453°
Liquid
Ni5As2
NiAs2 (?)
Ni11As8
NiAs
Schemotic
(β-NiAs2)
598°
590°
(α-NiAs2)
NiAs2
>1040°
~993°
962 ± 3°
895 ± 5°
23·4
?
830 ± 5°
~57
852 ± 3°
38·1
818 ± 5°
783 ± 5°
817°
β-NiAs2
590 ± 10°
598 ± 10°
α-NiAs2
< 250°

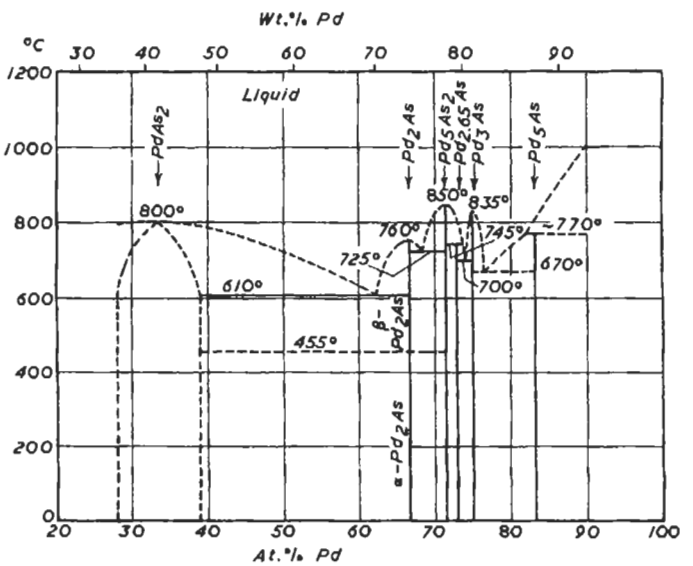
As–P



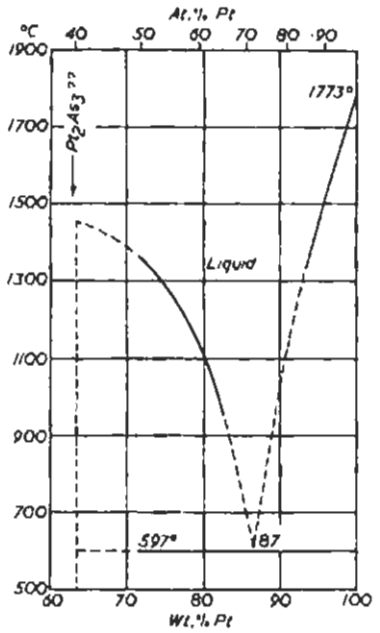
As–Pb



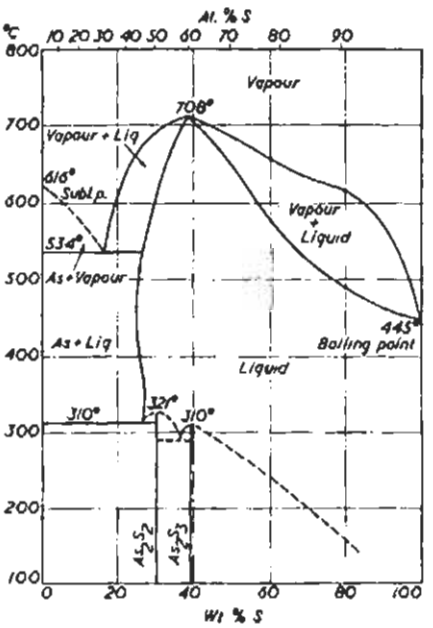
As–Pd



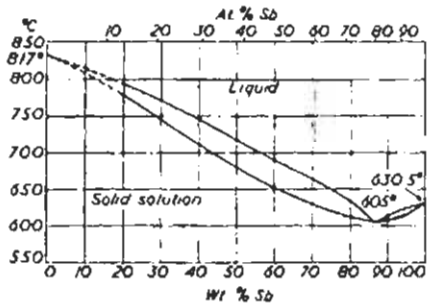
As–Pt



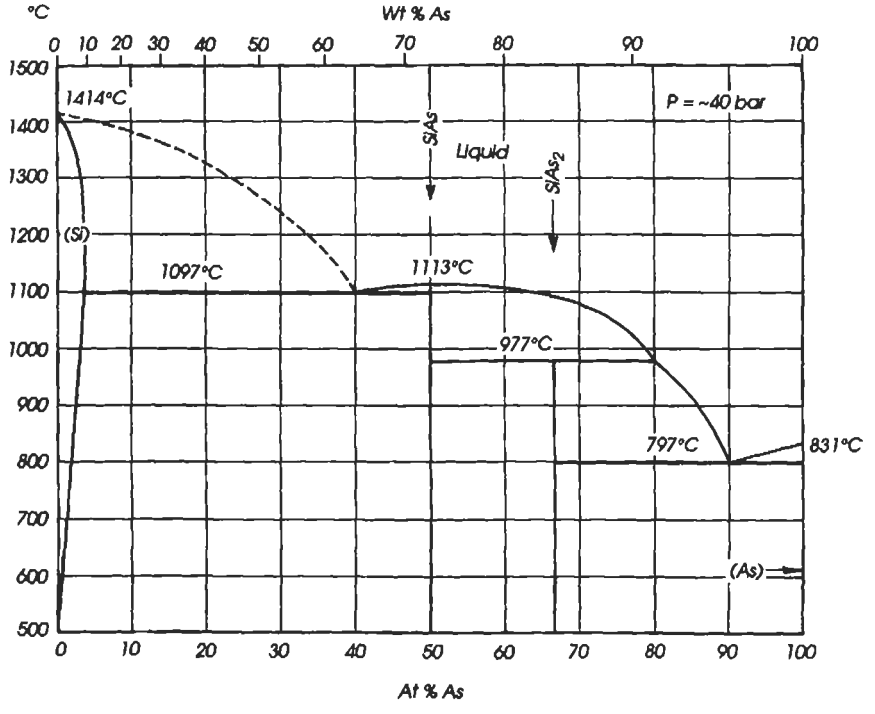
As–S



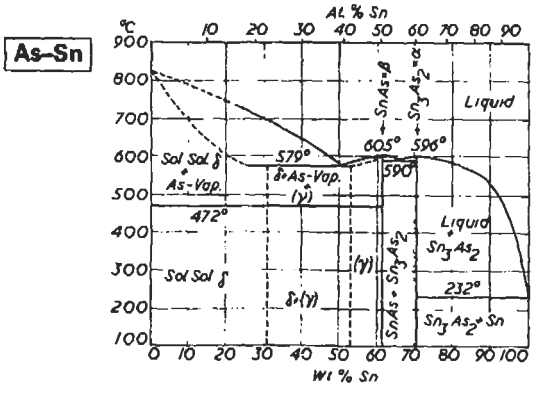
As–Sb



As–Si

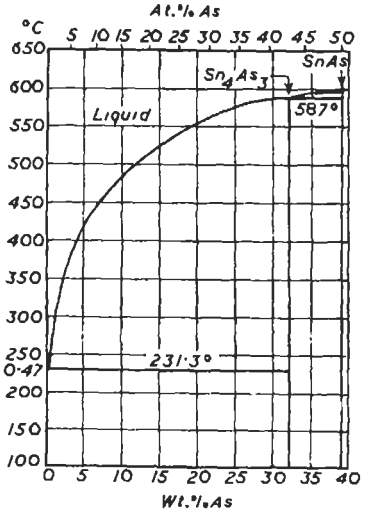


As–Sn

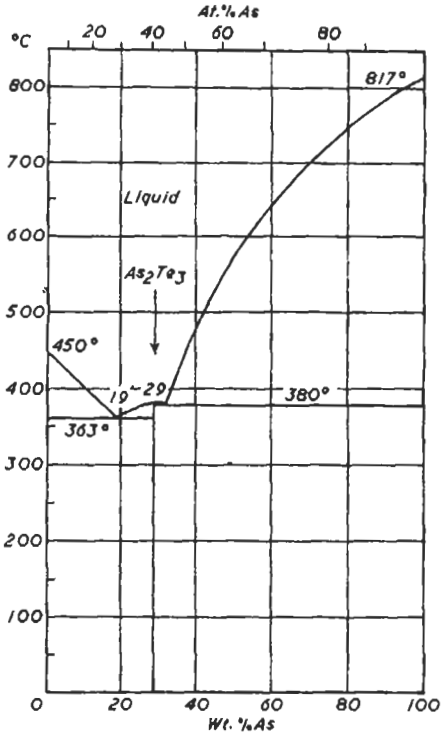


See alternative version of Sn-rich end

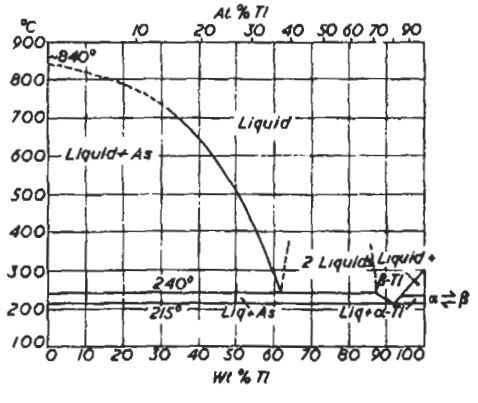
As–Sn



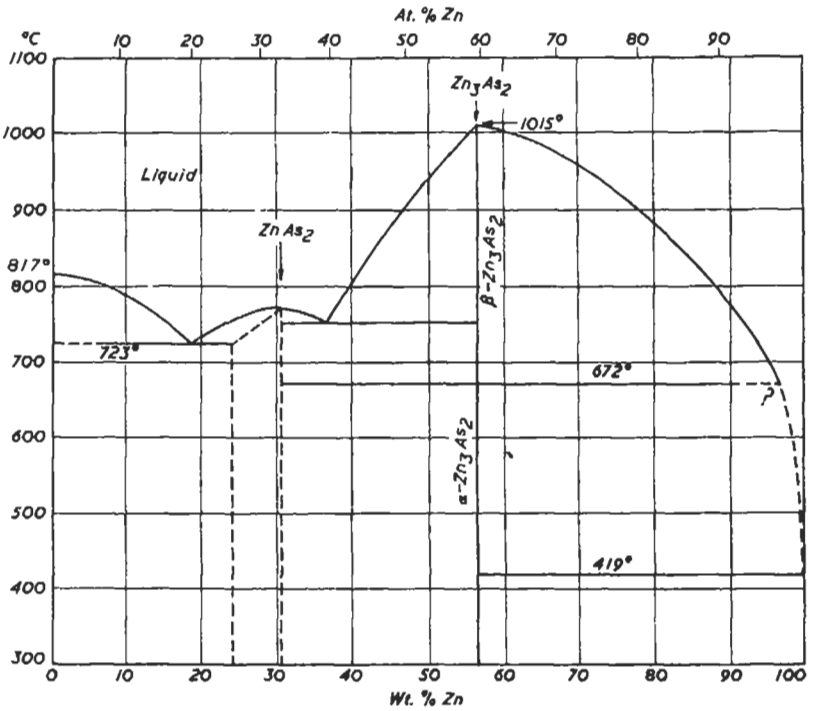
As–Te


At.% As
°C
20
40
60
80
800
700
600
500
400
300
200
100
0
817°
Liquid
As2Te3
450°
19~29
380°
363°
20
40
60
80
100
Wt. % As

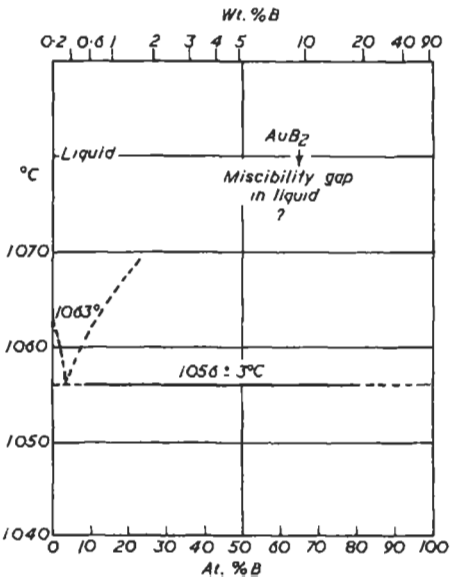
As–Tl


At % Tl
°C
10
20
30
40
50
60
70
90
900
800
700
600
500
400
300
200
100
840°
Liquid
Liquid + As
2 Liquids
Liquid + β-Tl
240°
215°
Liq + As
Liq + α-Tl
α ⇌ β
0
10
20
30
40
50
60
70
80
90
100
Wt % Tl

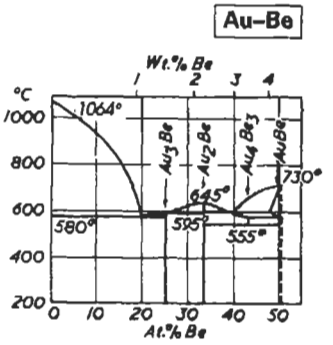
As–Zn



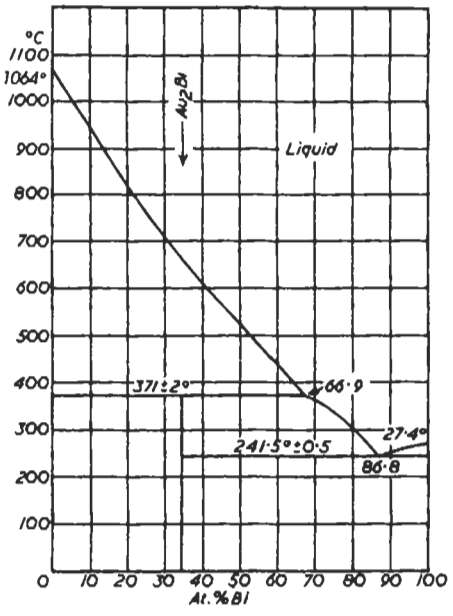
Au–B



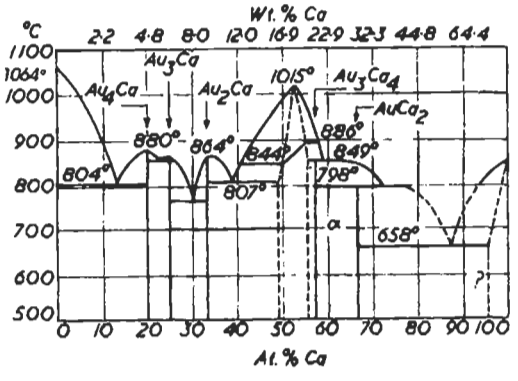
Au–Be



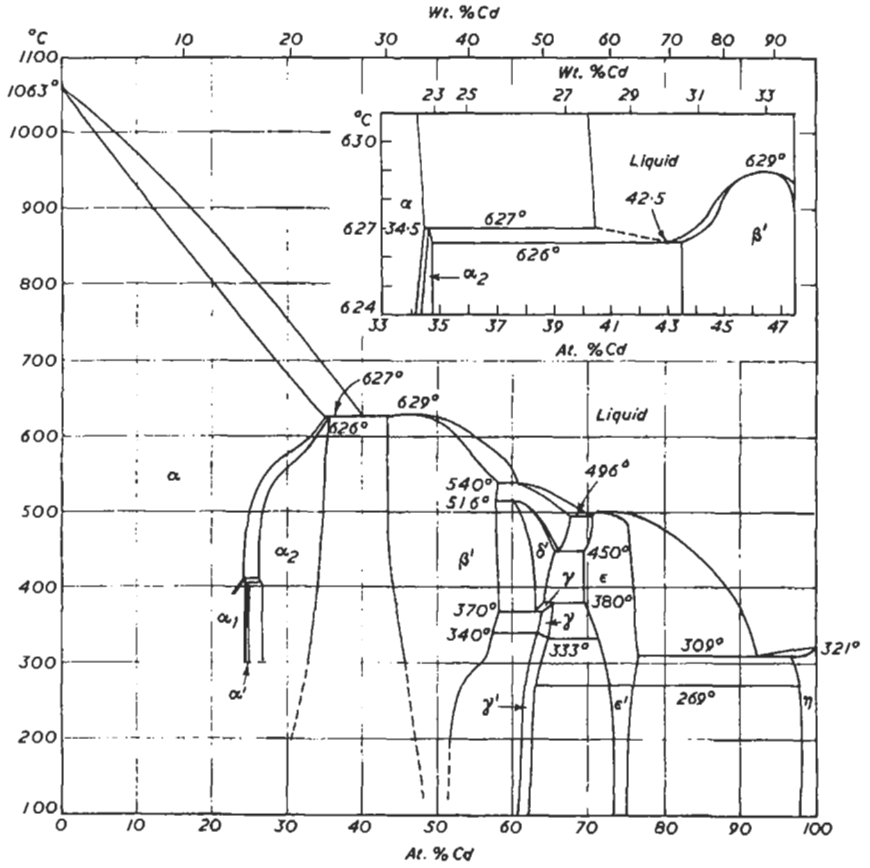
Au–Bi


°C
1100
1064°
1000
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
At. % Bi
Au2Bi
Liquid
371±2°
66·9
27·4°
241·5°±0·5
86·8

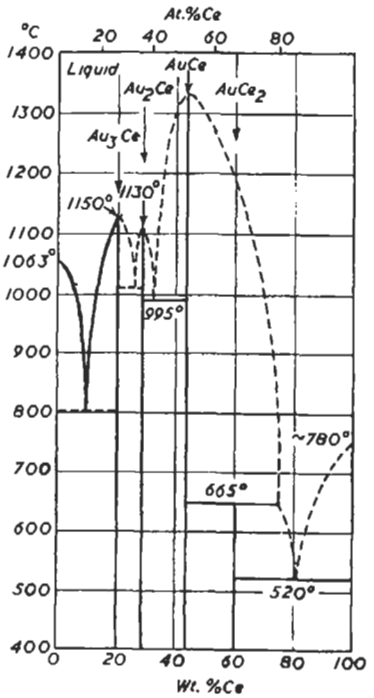
Au–Ca


Wt. % Ca
°C
2·2
4·8
8·0
12·0
16·9
22·9
32·3
44·8
64·4
1100
1064°
1000
900
800
700
600
500
Au4Ca
Au3Ca
Au2Ca
1015°
Au3Ca4
AuCa2
880°
864°
844°
886°
849°
804°
807°
798°
α
658°
β
0
10
20
30
40
50
60
70
80
90
100
At. % Ca

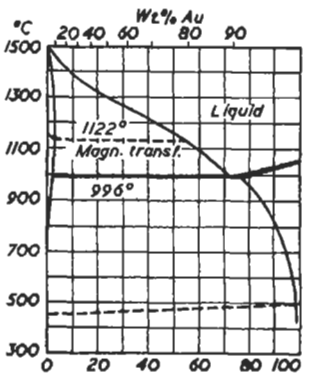
Au–Cd



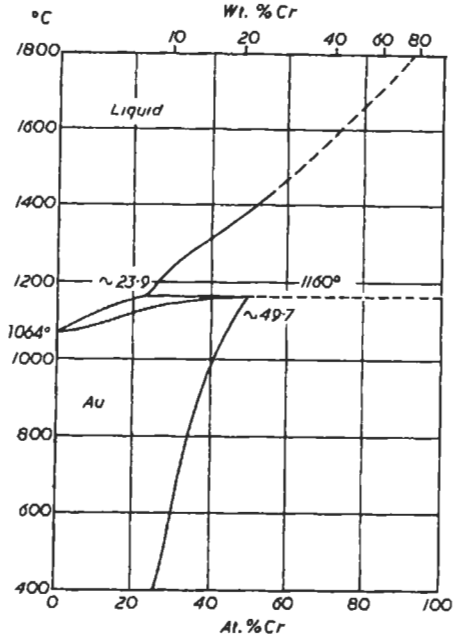
Au–Ce



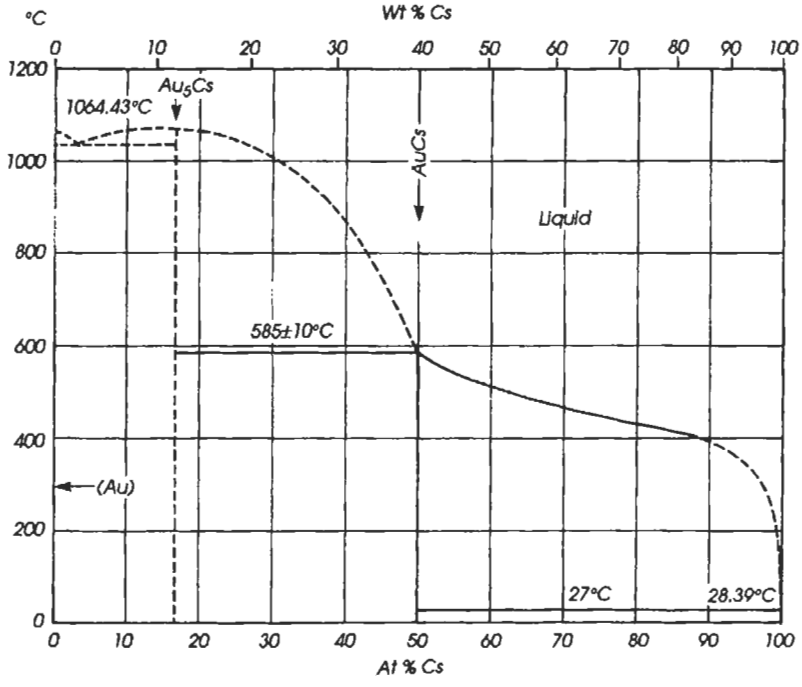
Au–Co



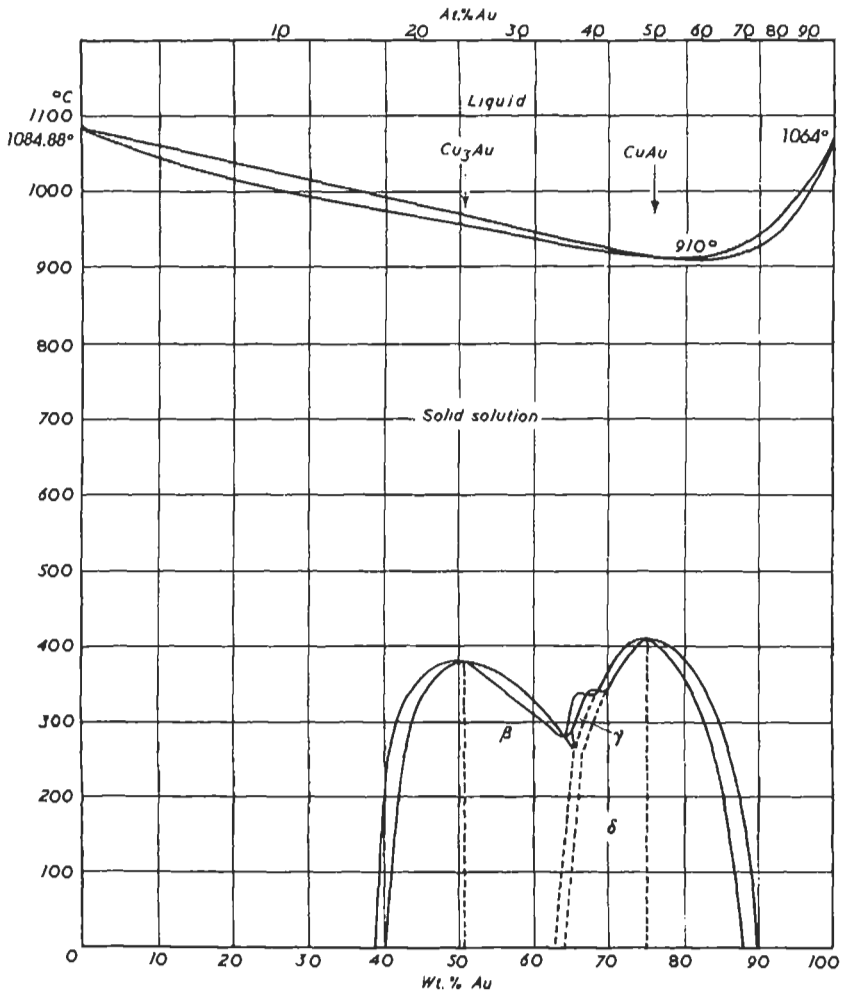
Au–Cr


°C
Wt. % Cr
10
20
40
60
80
1800
1600
1400
1200
1064°
1000
800
600
400
Liquid
~23·9
1160°
~49·7
Au
0
20
40
60
80
100
At. % Cr

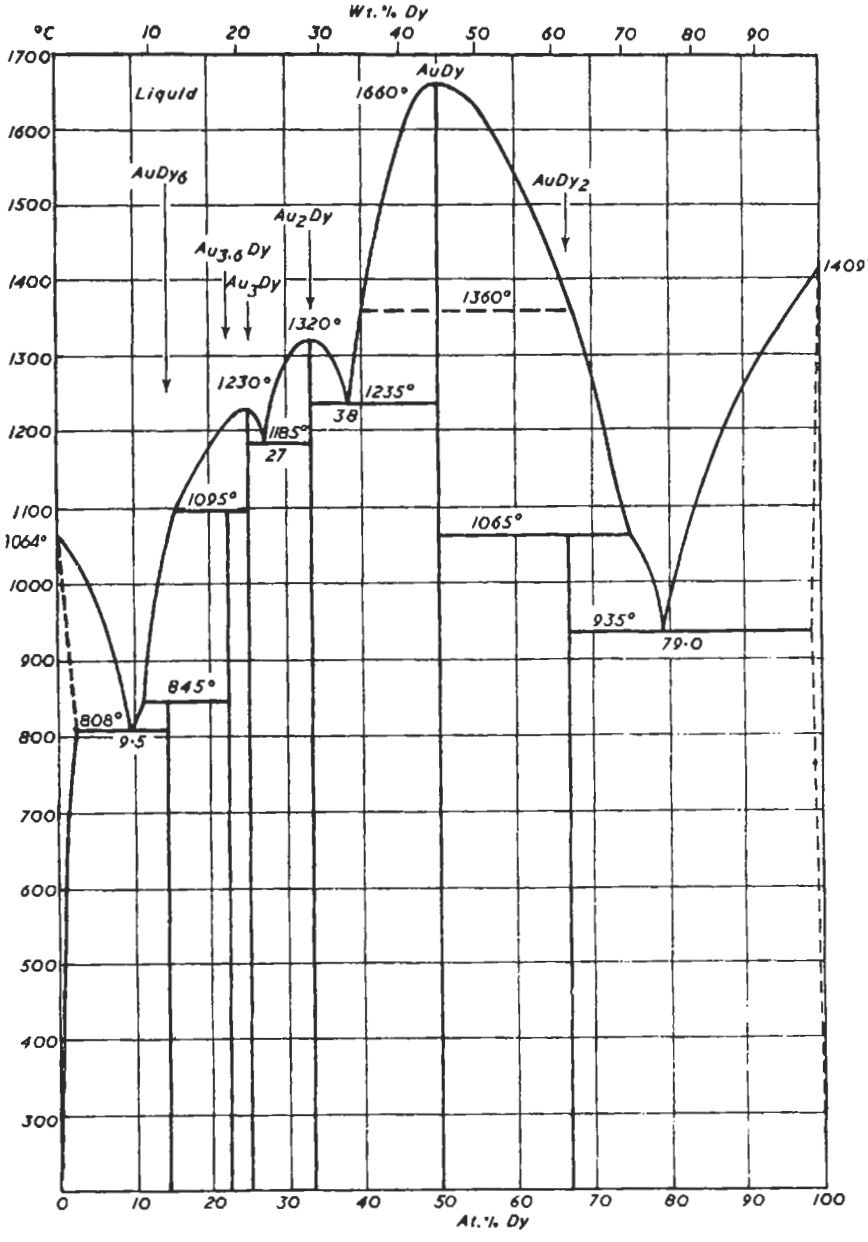
Au–Cs


°C
Wt % Cs
0
10
20
30
40
50
60
70
80
90
100
1200
1000
800
600
400
200
0
Au5Cs
1064.43°C
AuCs
Liquid
585±10°C
(Au)
27°C
28.39°C
At % Cs

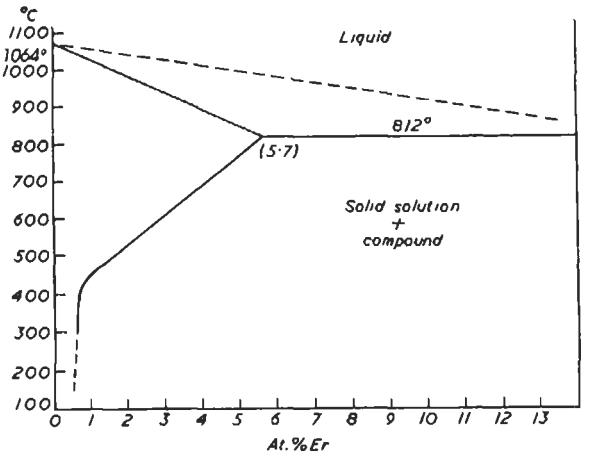
Au–Cu


At.% Au
10
20
30
40
50
60
70
80
90
°C
1100
1084.88°
1064°
910°
Liquid
Cu_3Au
CuAu
Solid solution
β
γ
δ
1000
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
Wt. % Au

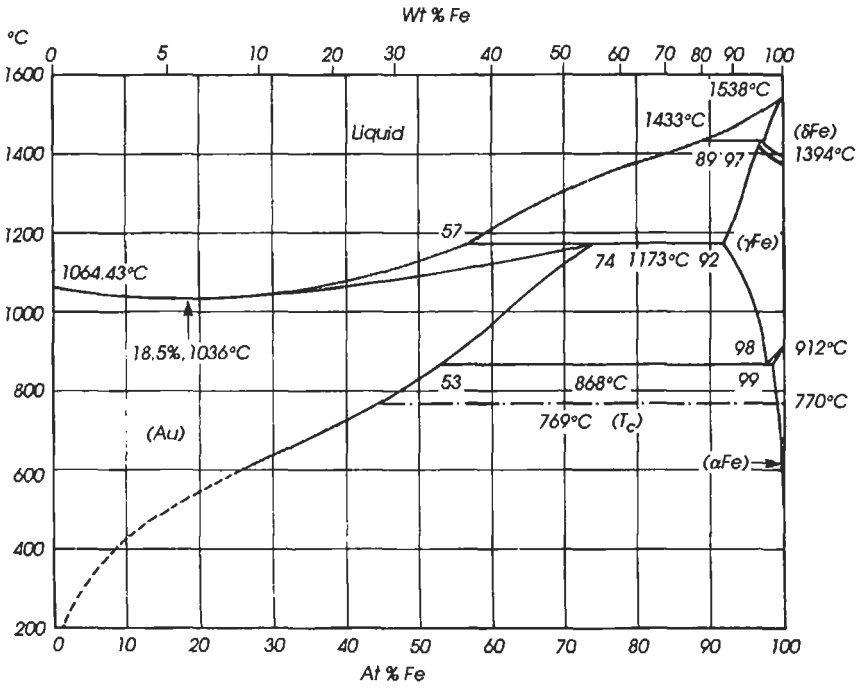
Au–Dy


°C
Wt. % Dy
At. % Dy
Liquid
AuDy
1660°
AuDy6
AuDy2
Au2Dy
Au3.6Dy
Au3Dy
1320°
1360°
1409°
1230°
1235°
38
1185°
27
1095°
1065°
1064°
935°
79·0
845°
808°
9·5

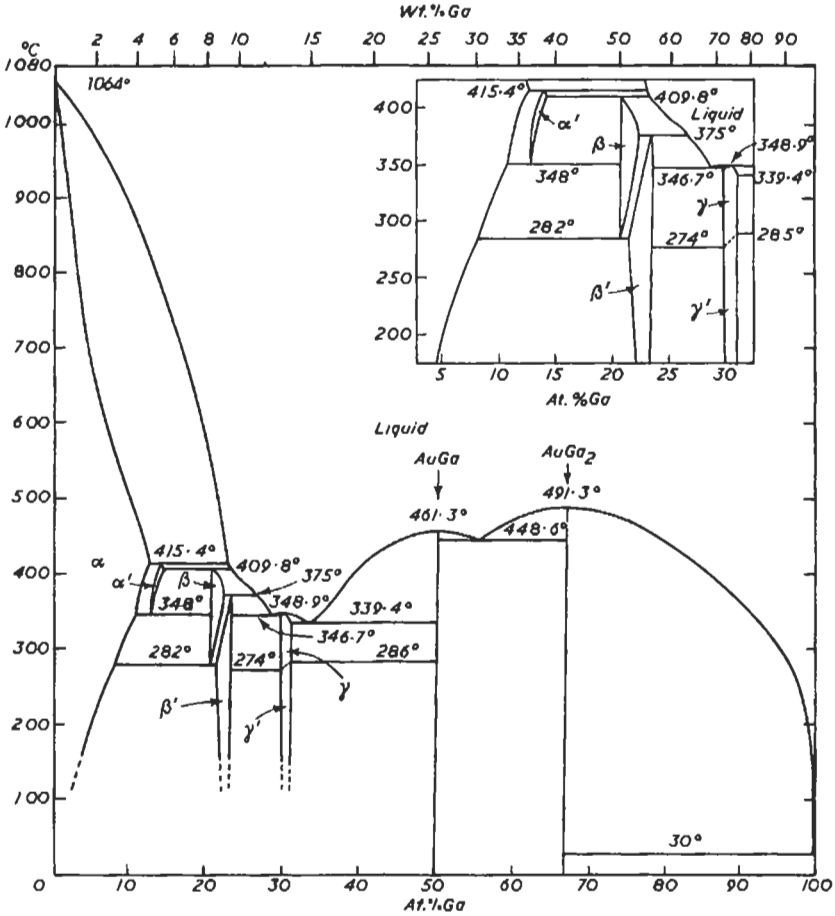
Au–Er


°C
1100
1064°
1000
900
800
700
600
500
400
300
200
100
Liquid
812°
(5·7)
Solid solution
+
compound
0 1 2 3 4 5 6 7 8 9 10 11 12 13
At.%Er

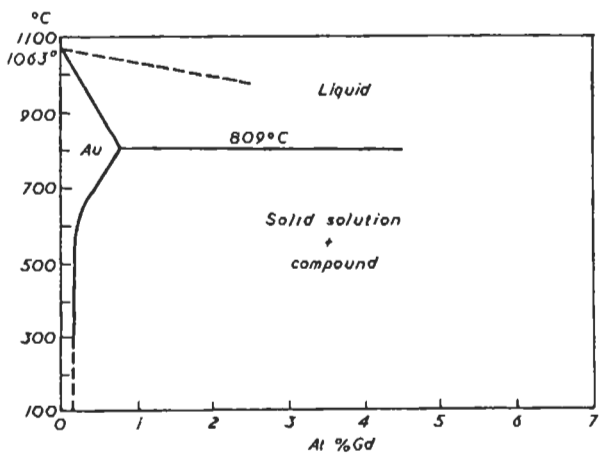
Au–Fe


Wt % Fe
°C
0 5 10 20 30 40 50 60 70 80 90 100
1600
1400
1200
1000
800
600
400
200
Liquid
1538°C
1433°C
(δFe)
1394°C
89·97
57
(γFe)
1064.43°C
74 1173°C 92
18.5%, 1036°C
98
912°C
53
868°C
99
770°C
769°C (Tc)
(Au)
(αFe)
0 10 20 30 40 50 60 70 80 90 100
At % Fe

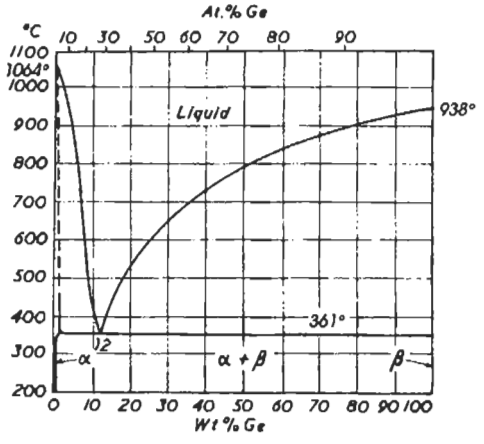
Au–Ga


Wt.% Ga
°C
1064°
415·4°
409·8°
375°
348·9°
339·4°
346·7°
348°
282°
274°
285°
Liquid
AuGa
AuGa2
461·3°
491·3°
448·6°
30°
α
α'
β
β'
γ
γ'
At. %Ga

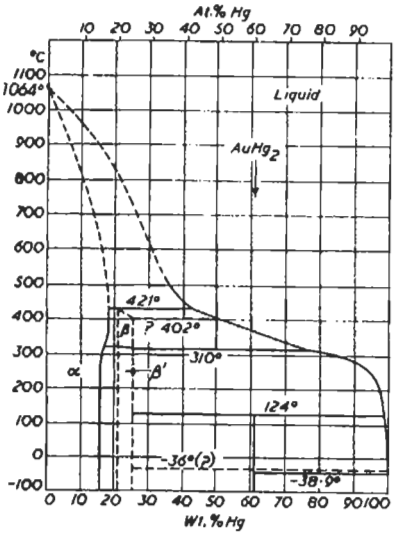
Au–Gd


°C
1063°
Liquid
809°C
Au
Solid solution
+
compound
At %Gd

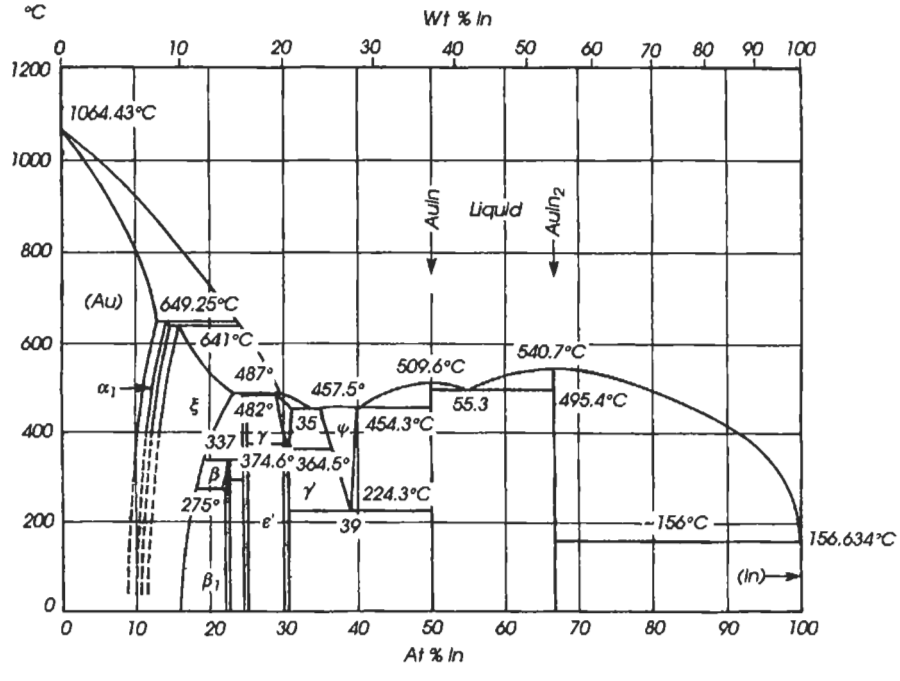
Au–Ge



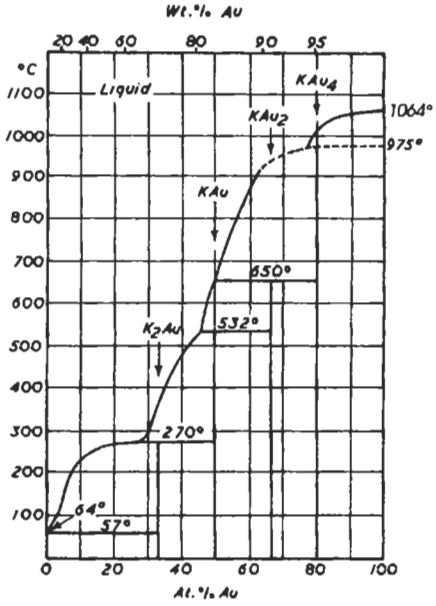
Au–Hg



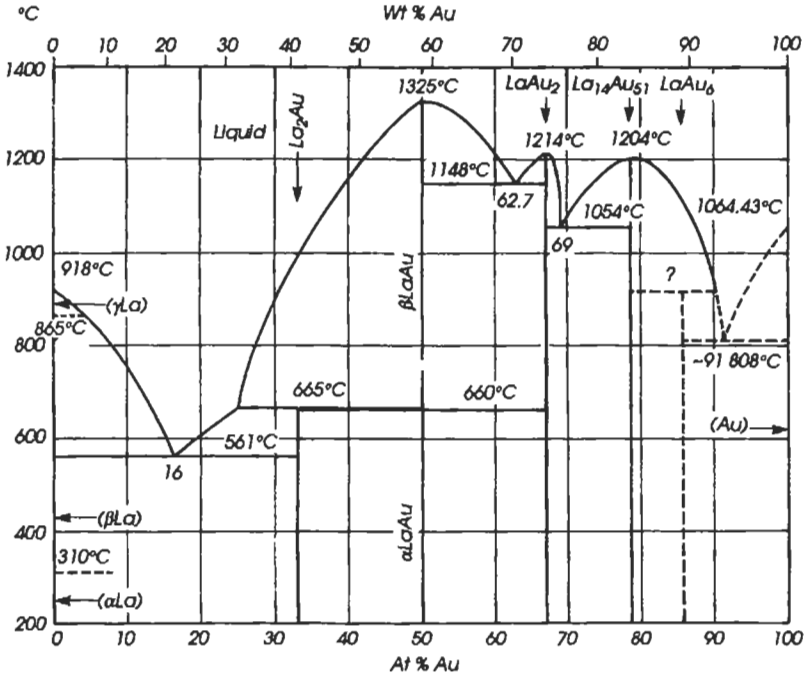
Au–In



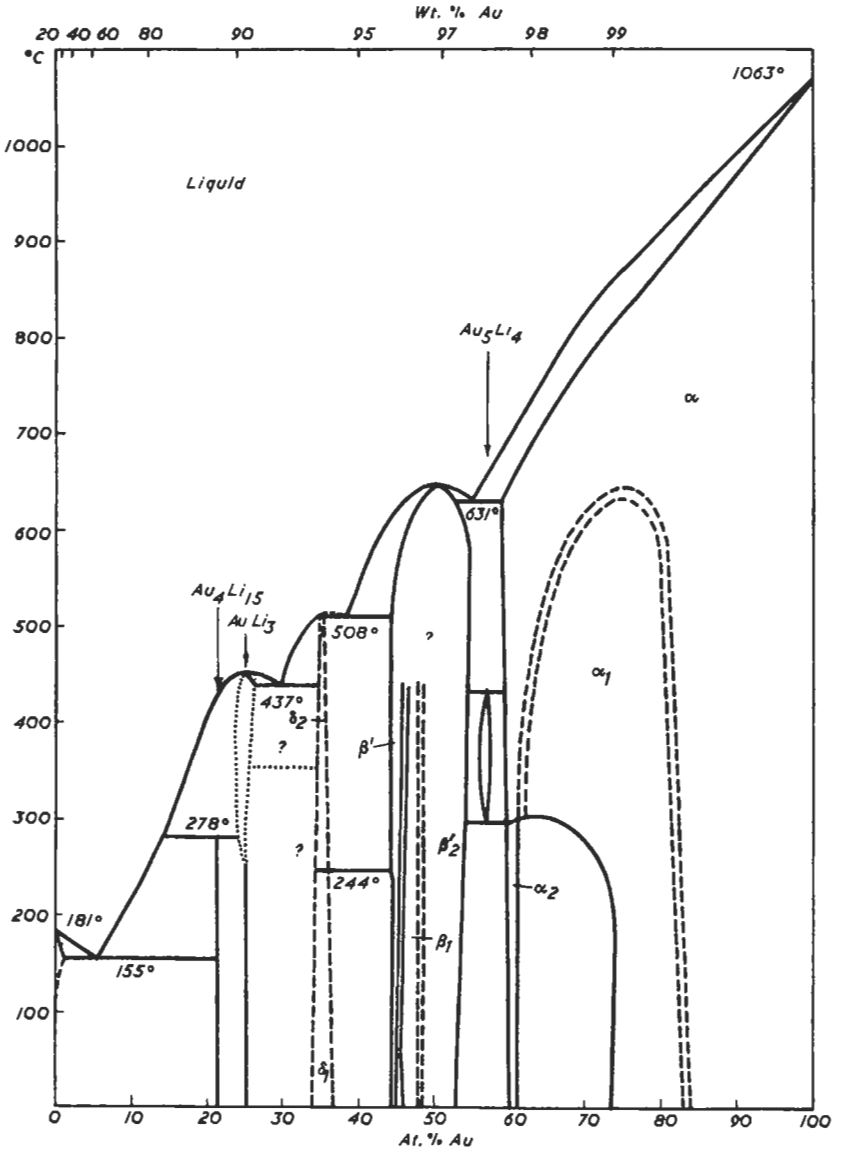
Au–K


Wt.% Au
20 40 60 80 90 95
°C
1100
1000
900
800
700
600
500
400
300
200
100
Liquid
KAu4
KAu2
KAu
K2Au
1064°
975°
650°
532°
270°
64°
57°
0 20 40 60 80 100
At.% Au

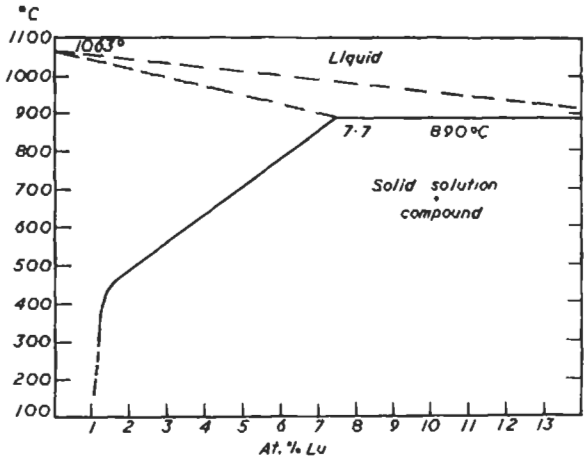
Au–La


°C
Wt % Au
0 10 20 30 40 50 60 70 80 90 100
1400
1200
1000
800
600
400
200
Liquid
La2Au
1325°C
LaAu2
La14Au51
LaAu6
1214°C
1204°C
1148°C
62.7
1054°C
69
1064.43°C
?
~91 808°C
(Au)
918°C
(γLa)
865°C
665°C
660°C
561°C
16
(βLa)
310°C
(αLa)
βLaAu
αLaAu
At % Au

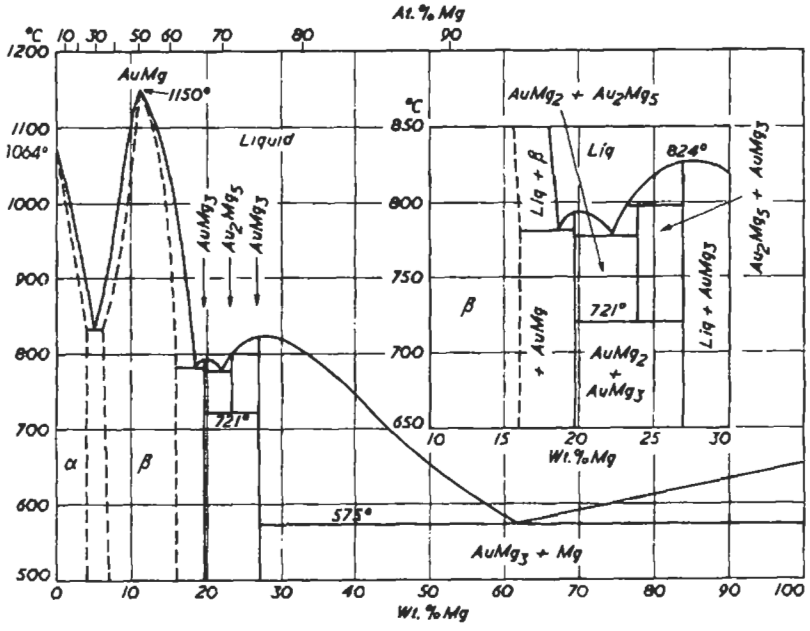
Au–Li


Wt. % Au
20 40 60 80 90 95 97 98 99
°C
1063°
Liquid
Au5Li4
α
631°
Au4Li15
Au Li3
508°
?
437°
δ2
?
β'
α1
278°
?
β'2
244°
α2
181°
β1
155°
δ1
0 10 20 30 40 50 60 70 80 90 100
At. % Au

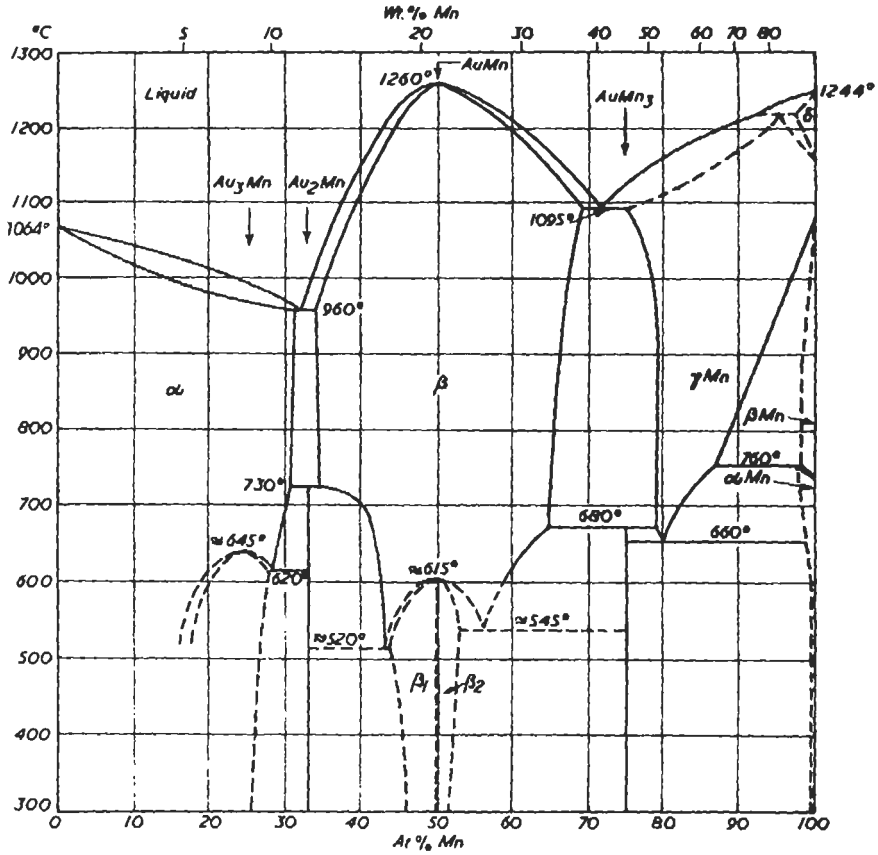
Au–Lu


°C
1100
1000
900
800
700
600
500
400
300
200
100
1063°
Liquid
7·7
890°C
Solid solution
compound
1 2 3 4 5 6 7 8 9 10 11 12 13
At. % Lu

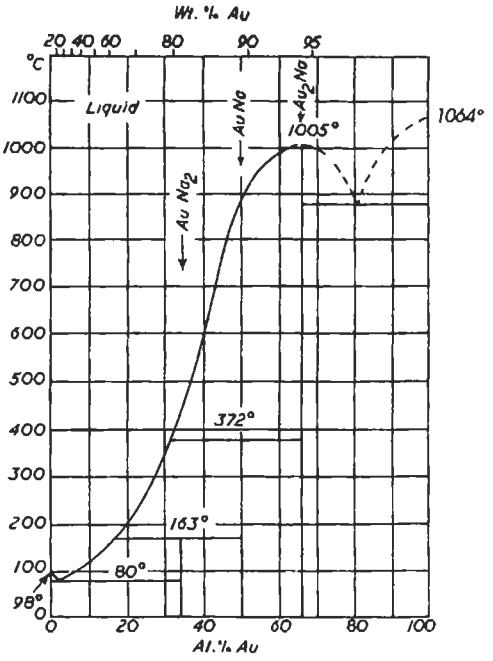
Au–Mg


At. % Mg
°C 10 30 50 60 70 80 90
1200
1100
1064°
1000
900
800
700
600
500
AuMg
1150°
Liquid
AuMg3
Au2Mg5
AuMg3
721°
α
β
575°
AuMg3 + Mg
0 10 20 30 40 50 60 70 80 90 100
Wt. % Mg
°C
850
800
750
700
650
AuMg2 + Au2Mg5
Liq
824°
Liq + β
β
AuMg + AuMg2
721°
AuMg2 + AuMg3
Liq + AuMg3
Au2Mg5 + AuMg3
10 15 20 25 30
Wt. % Mg

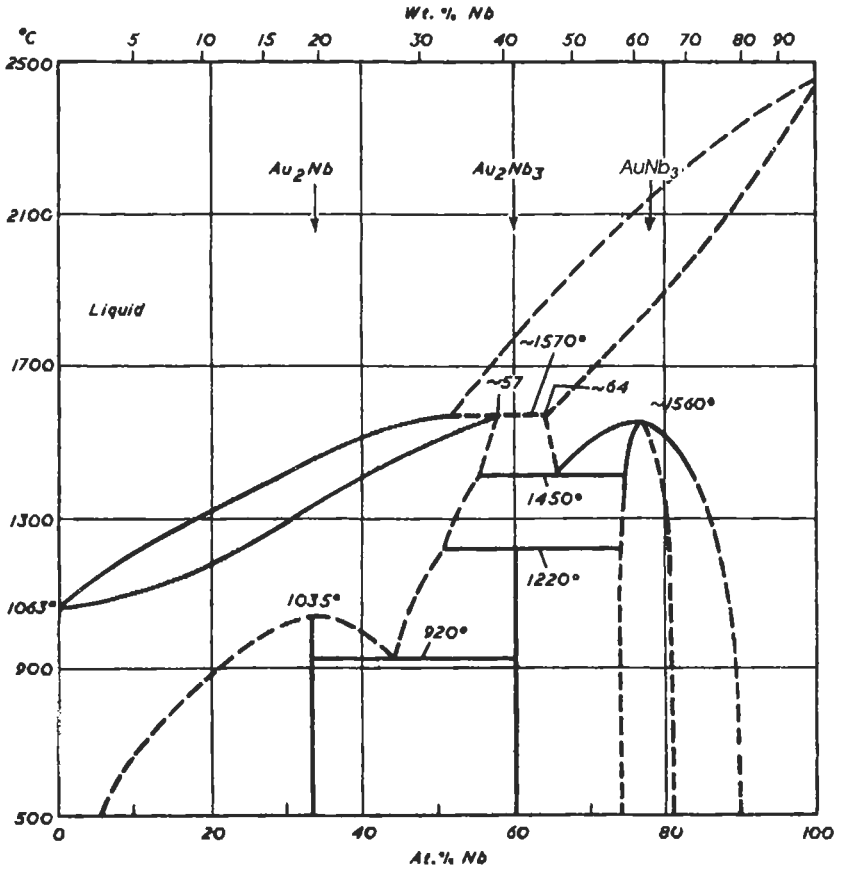
Au–Mn


Wt. % Mn
°C
5
10
20
30
40
50
60
70
80
1300
1200
1100
1064°
1000
900
800
700
600
500
400
300
Liquid
1260°
AuMn
AuMn3
1244°
δ
Au3Mn
Au2Mn
1095°
960°
α
β
γMn
βMn
780°
αMn
730°
680°
660°
≈645°
620°
≈615°
≈545°
≈520°
β1
β2
0
10
20
30
40
50
60
70
80
90
100
At % Mn

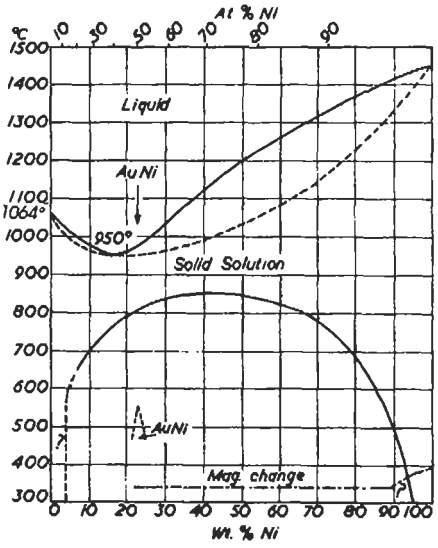
Au–Na


Wt. % Au
20 40 60 80 90 95
°C
1100
1000
900
800
700
600
500
400
300
200
100
98°
0
Liquid
Au Na
Au Na2
Au2Na
1005°
1064°
372°
163°
80°
0 20 40 60 80 100
At.% Au

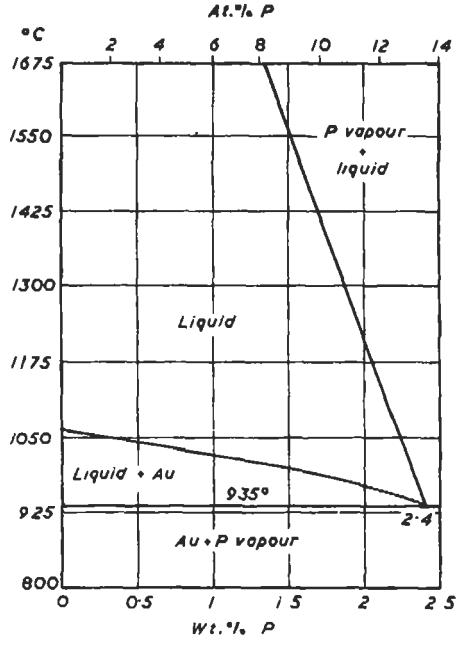
Au–Nb


Wt. % Nb
°C
5 10 15 20 30 40 50 60 70 80 90
2500
2100
1700
1300
1063°
900
500
Au2Nb
Au2Nb3
AuNb3
Liquid
~1570°
~57
~64
~1560°
1450°
1220°
1035°
920°
0 20 40 60 80 100
At.% Nb

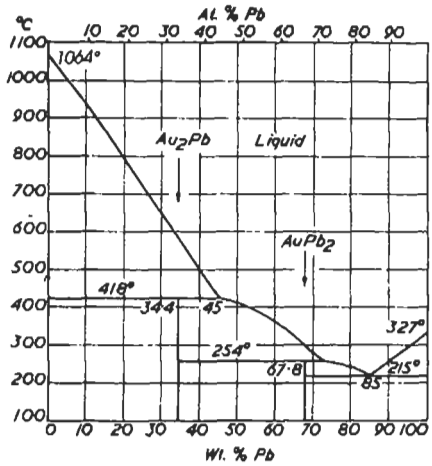
Au–Ni


°C
At % Ni
1500
1400
1300
1200
1100
1064°
1000
900
800
700
600
500
400
300
Liquid
AuNi
950°
Solid Solution
AuNi
Mag. change
0 10 20 30 40 50 60 70 80 90 100
Wt. % Ni

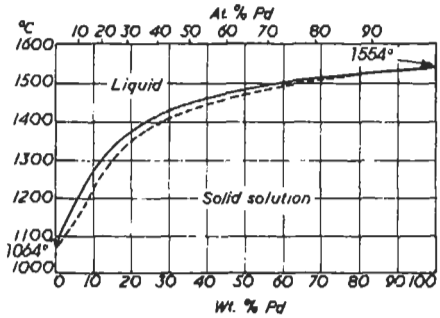
Au–P


At.% P
°C
1675
1550
1425
1300
1175
1050
925
800
P vapour + liquid
Liquid
Liquid + Au
935°
2·4
Au + P vapour
0 0·5 1 1·5 2 2·5
Wt.% P

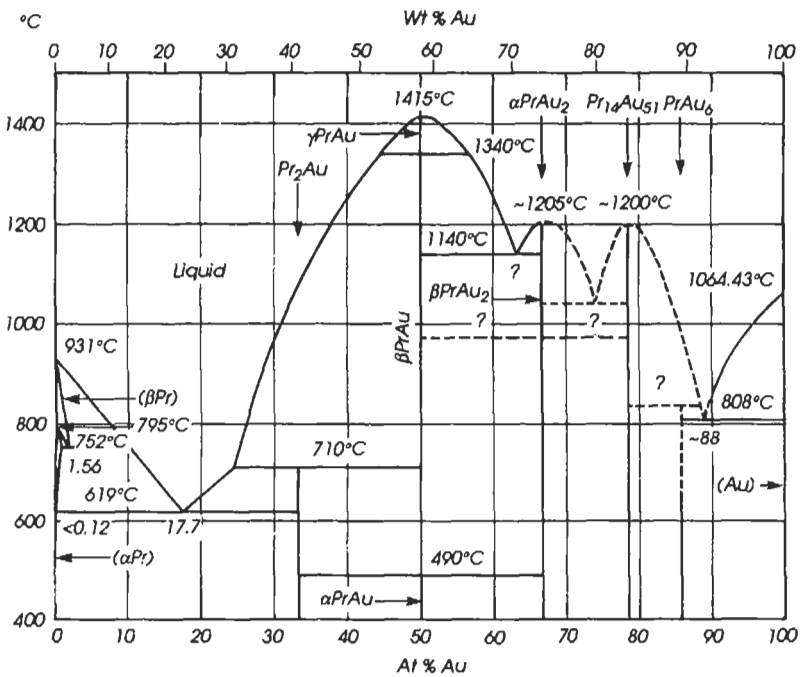
Au–Pb



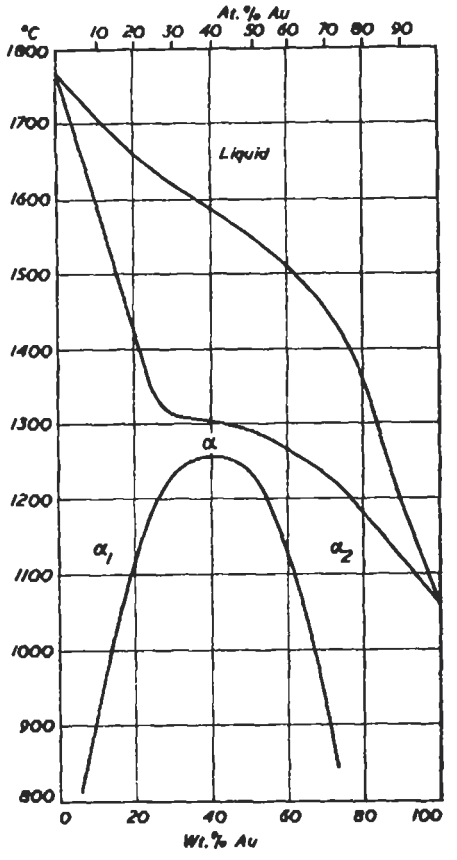
Au–Pd



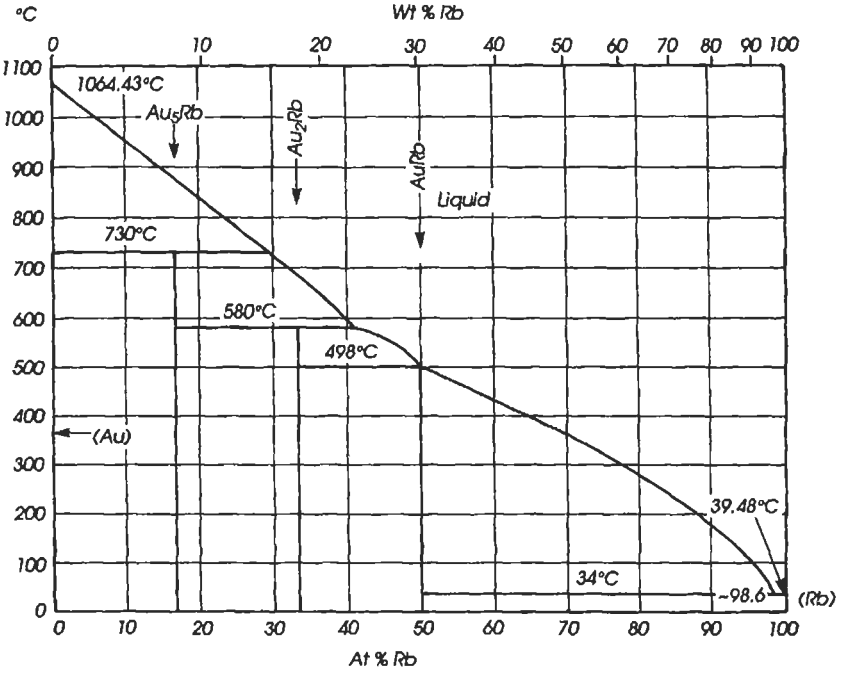
Au–Pr



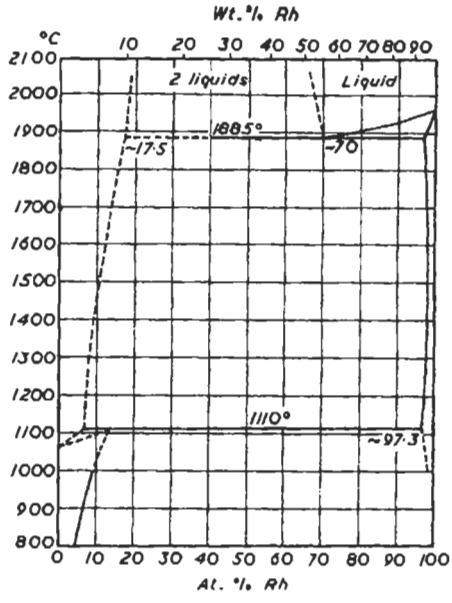
Au–Pt


At. % Au
°C
10 20 30 40 50 60 70 80 90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
Liquid
α
α_1
α_2
0 20 40 60 80 100
Wt. % Au

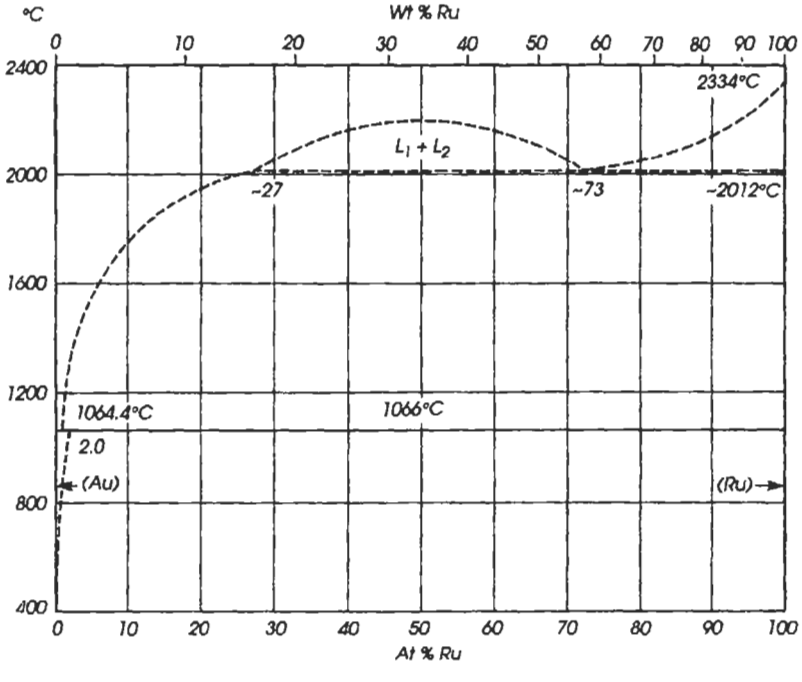
Au–Rb


°C
Wt % Rb
0 10 20 30 40 50 60 70 80 90 100
1100
1000
900
800
700
600
500
400
300
200
100
0
1064.43°C
Au_5Rb
Au_2Rb
AuRb
Liquid
730°C
580°C
498°C
(Au)
39.48°C
34°C
~98.6
(Rb)
0 10 20 30 40 50 60 70 80 90 100
At % Rb

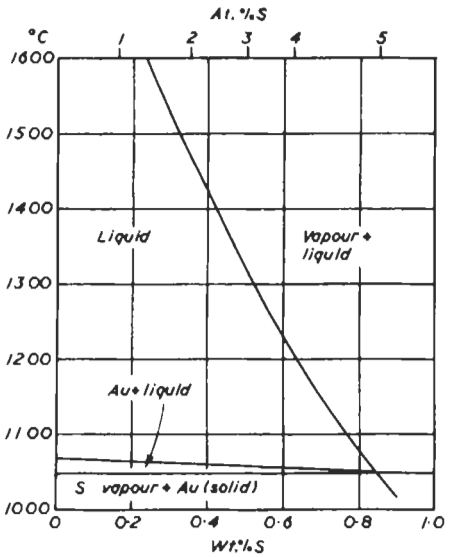
Au–Rh


Wt. % Rh
°C
2 liquids
Liquid
1885°
~17.5
~70
1110°
~97.3
At. % Rh

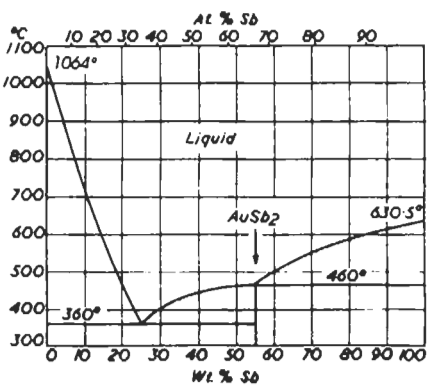
Au–Ru


°C
Wt % Ru
2334°C
$L_1 + L_2$
~27
~73
~2012°C
1064.4°C
1066°C
2.0
(Au)
(Ru)
At % Ru

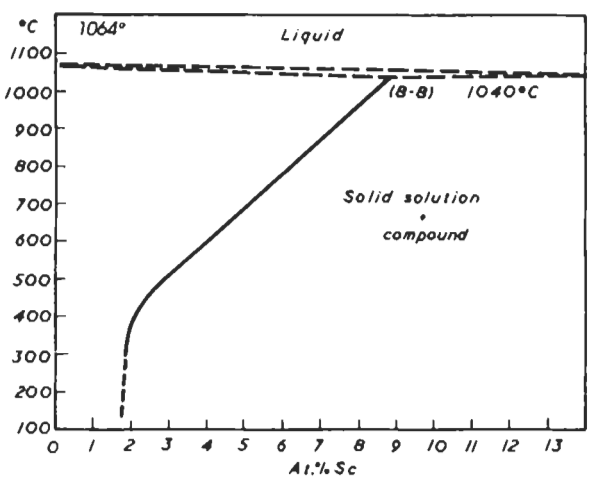
Au–S



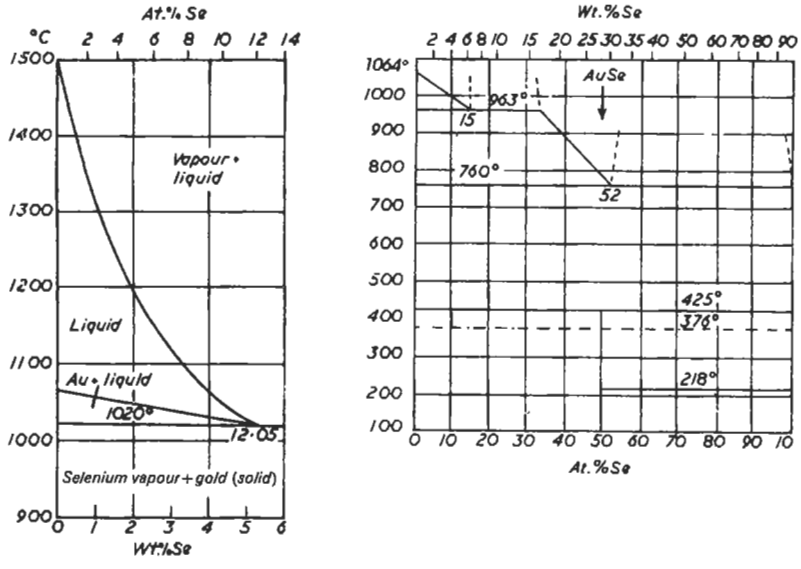
Au–Sb



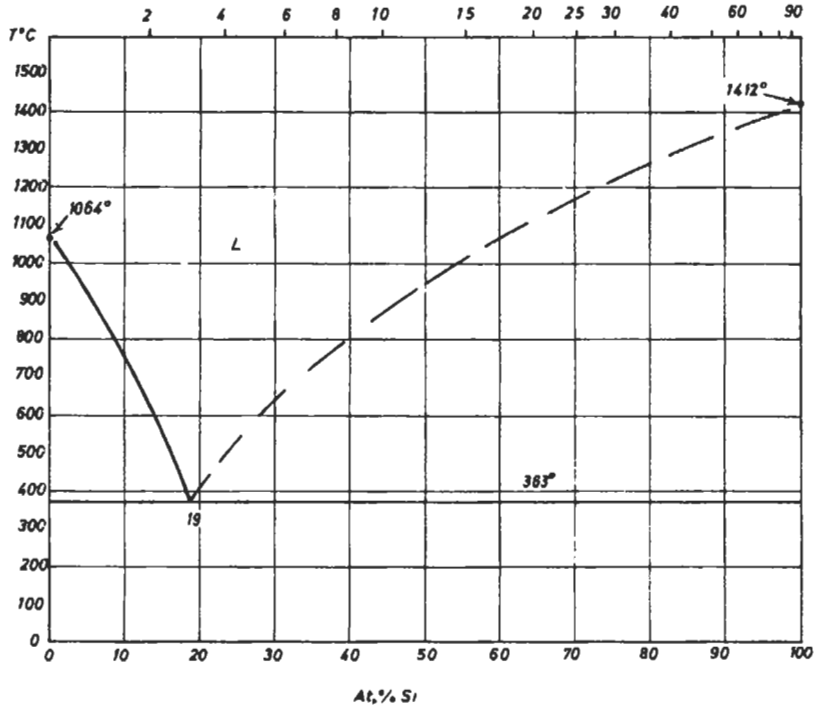
Au–Sc



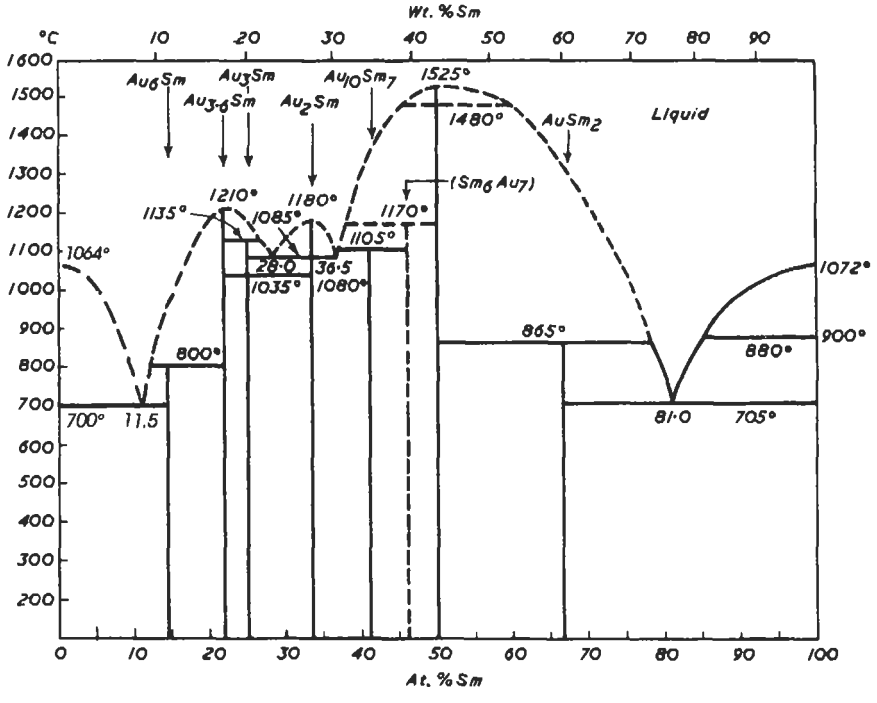
Au–Se


At.% Se
°C
2 4 6 8 10 12 14
1500
1400
1300
1200
1100
1000
900
Vapour + liquid
Liquid
Au + liquid
1020°
12·05
Selenium vapour + gold (solid)
0 1 2 3 4 5 6
Wt.% Se
Wt.% Se
2 4 6 8 10 15 20 25 30 35 40 50 60 70 80 90
1064°
1000
900
800
700
600
500
400
300
200
100
AuSe
963°
15
760°
52
425°
376°
218°
0 10 20 30 40 50 60 70 80 90 10
At.% Se

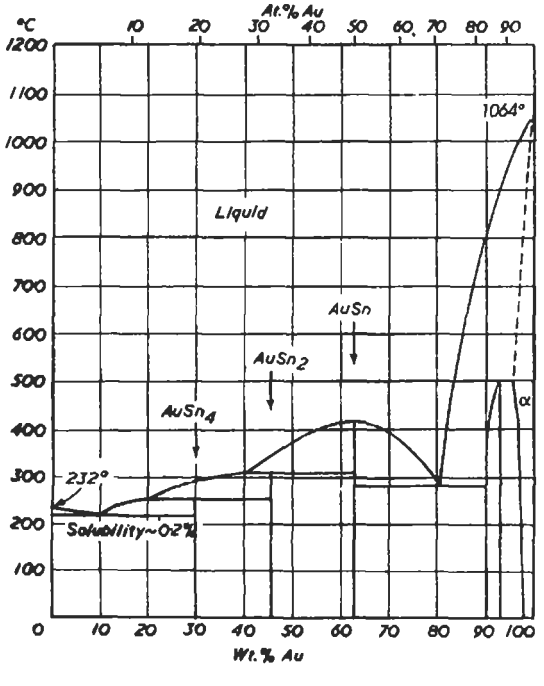
Au–Si


Wt.% Si
2 4 6 8 10 15 20 25 30 40 60 90
T°C
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
1064°
L
1412°
383°
19
0 10 20 30 40 50 60 70 80 90 100
At.% Si

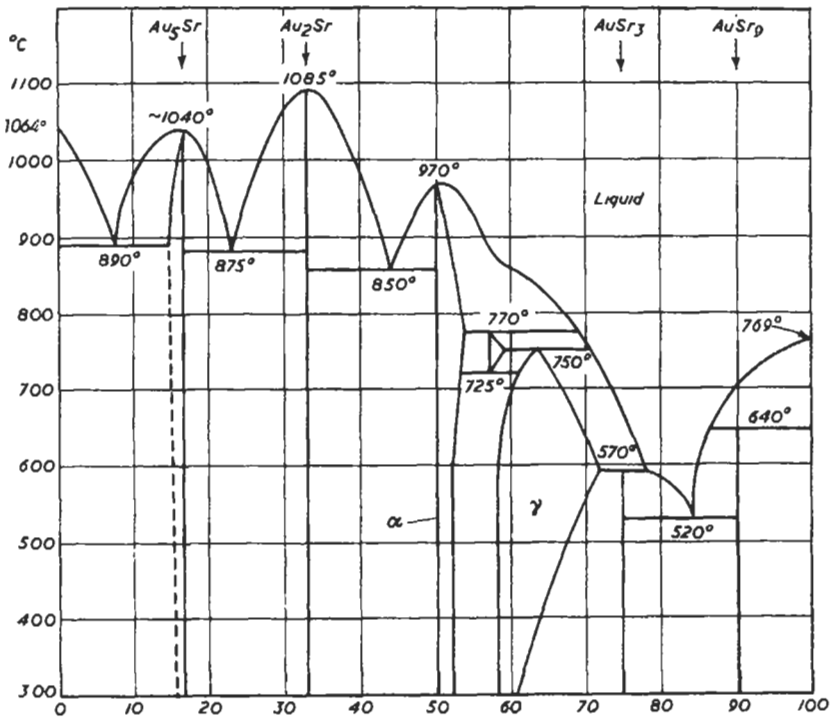
Au–Sm


Wt. % Sm
°C
Au6Sm
Au3Sm
Au3-6Sm
Au2Sm
Au10Sm7
1525°
1480°
AuSm2
Liquid
(Sm6Au7)
1210°
1180°
1135°
1085°
1170°
1105°
1064°
28·0
36·5
1035°
1080°
1072°
865°
900°
880°
800°
700°
11.5
81·0
705°
At. % Sm

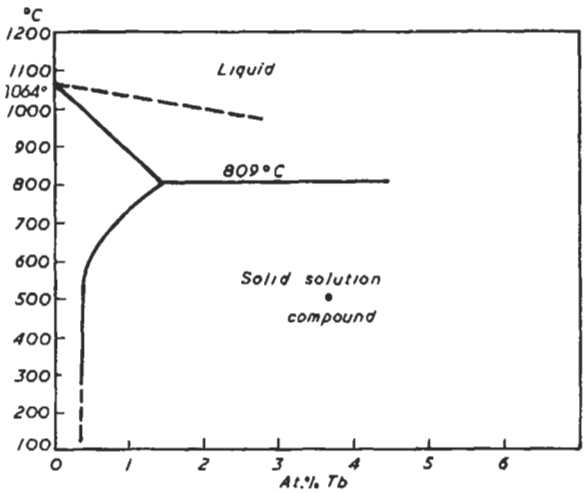
Au–Sn


At.% Au
°C
1064°
Liquid
AuSn
AuSn2
AuSn4
α
232°
Solubility~0·2%
Wt.% Au

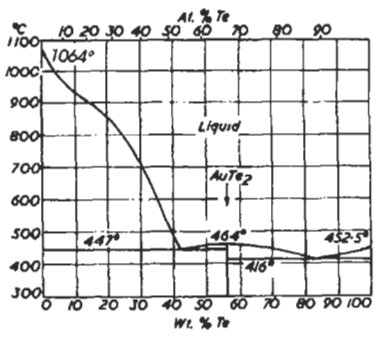
Au–Sr



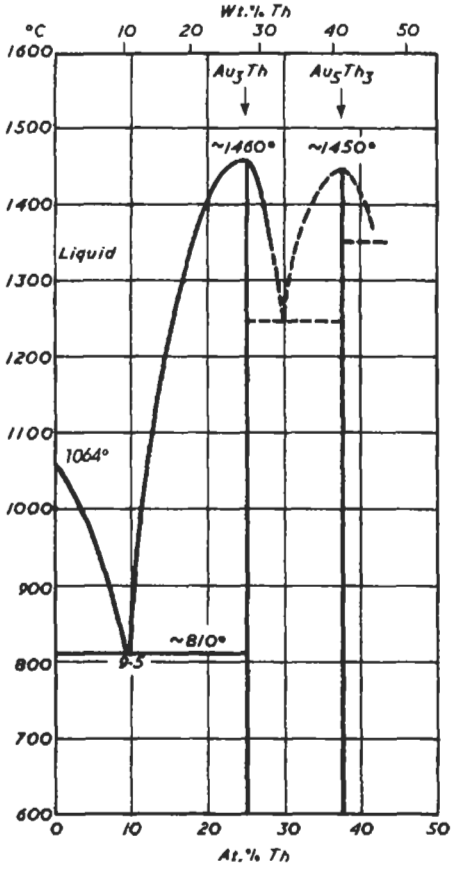
Au–Tb



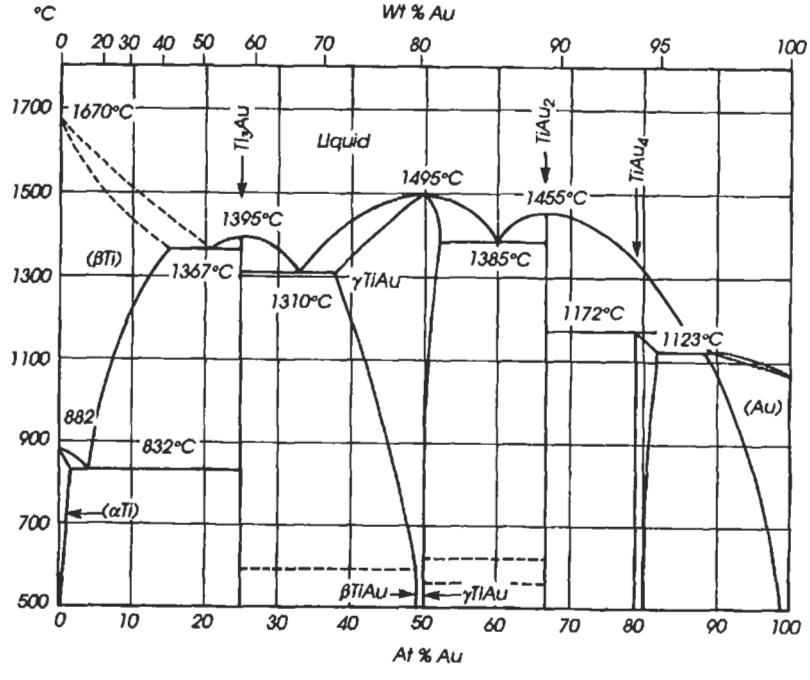
Au–Te



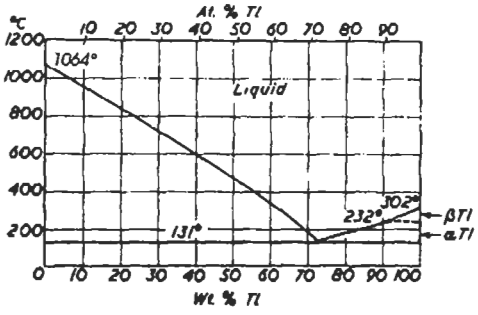
Au–Th


Wt.% Th
°C
10
20
30
40
50
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
Au3Th
Au5Th3
~1460°
~1450°
Liquid
1064°
~810°
0-3
0
10
20
30
40
50
At.% Th

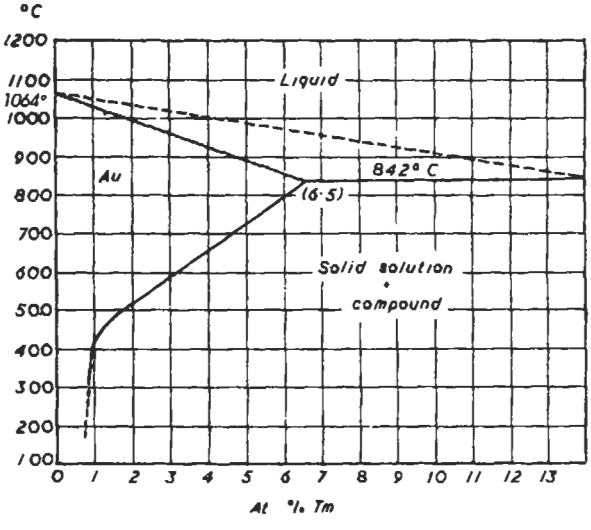
Au–Ti


°C
Wt % Au
0
20
30
40
50
60
70
80
90
95
100
1700
1500
1300
1100
900
700
500
1670°C
Ti3Au
Liquid
TiAu2
TiAu4
1495°C
1455°C
1395°C
(βTi)
1367°C
1385°C
γTiAu
1310°C
1172°C
1123°C
882
832°C
(Au)
(αTi)
βTiAu
γTiAu
0
10
20
30
40
50
60
70
80
90
100
At % Au

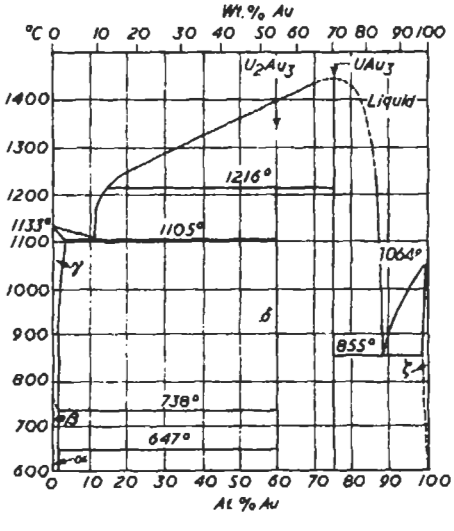
Au–Tl



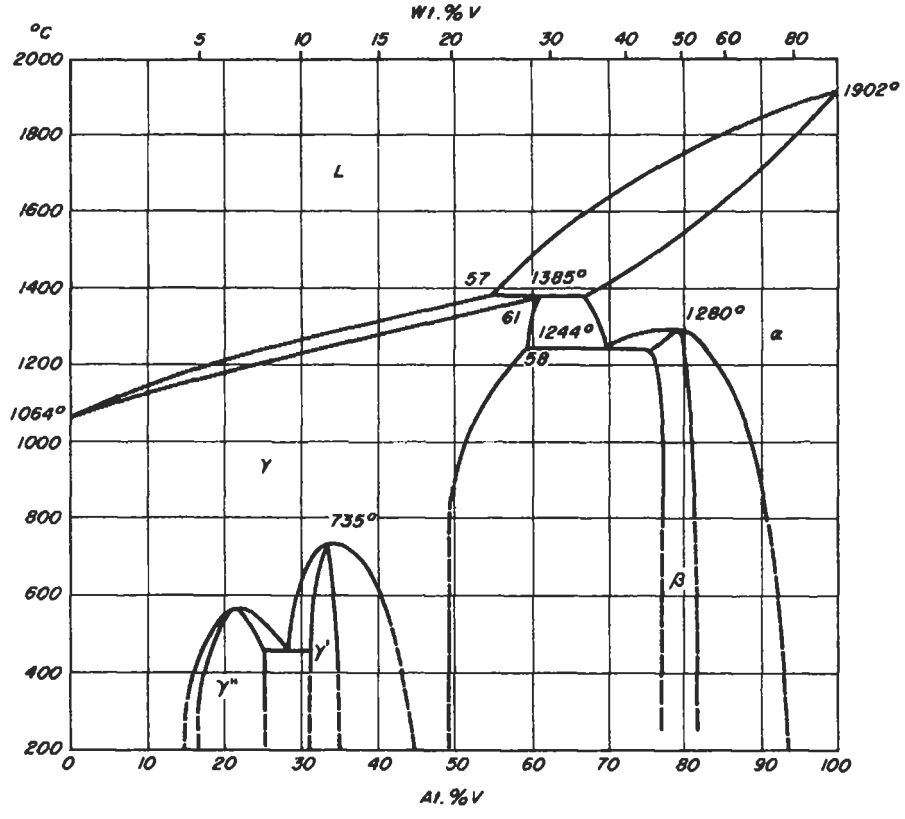
Au–Tm



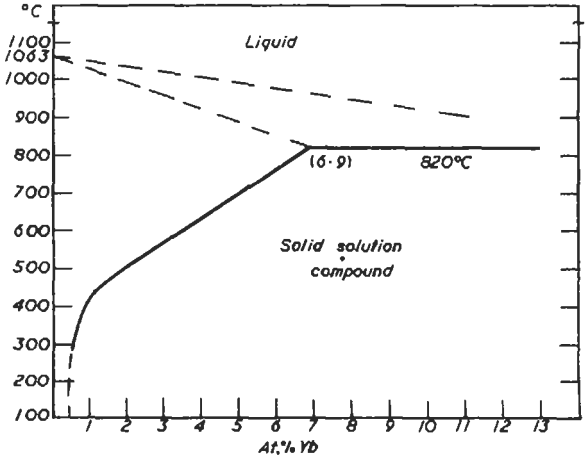
Au–U



Au–V

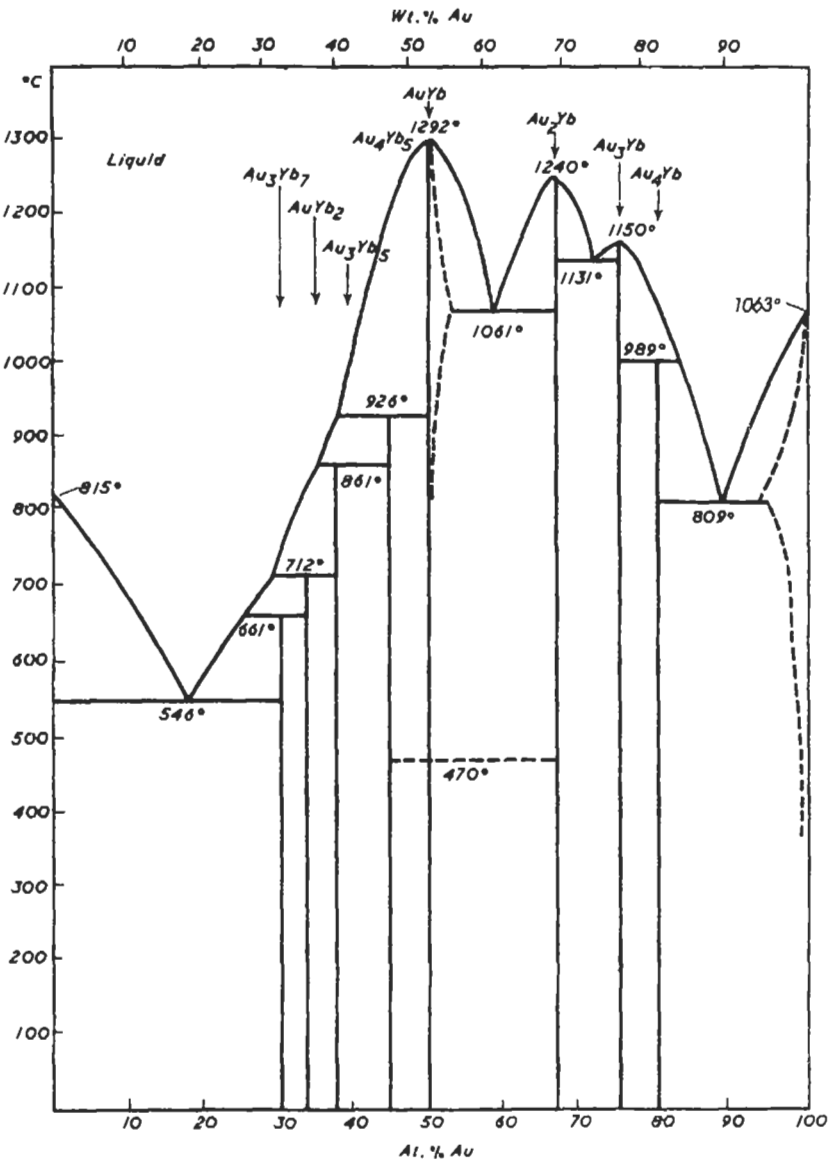


Au–Yb

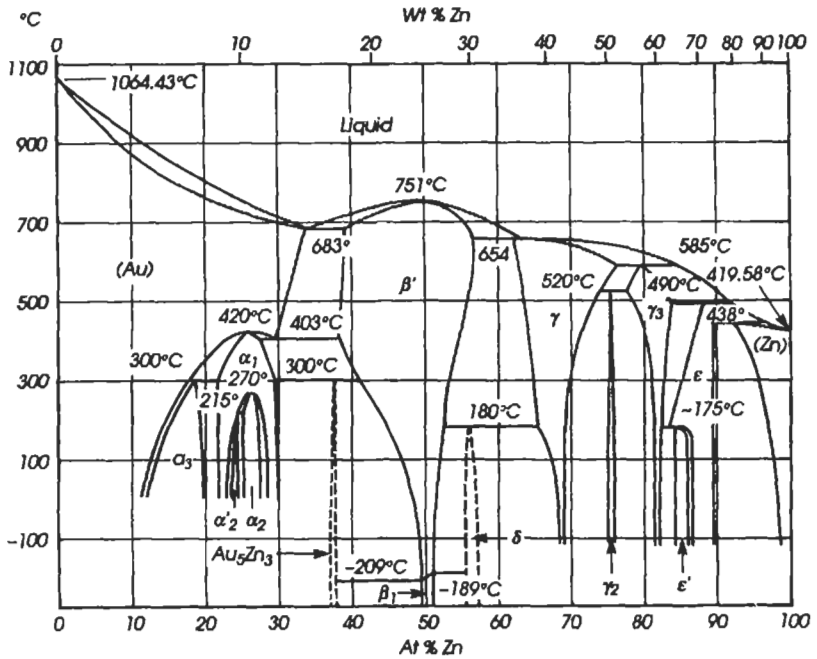


See complete Au-Yb diagram on page **11–93**

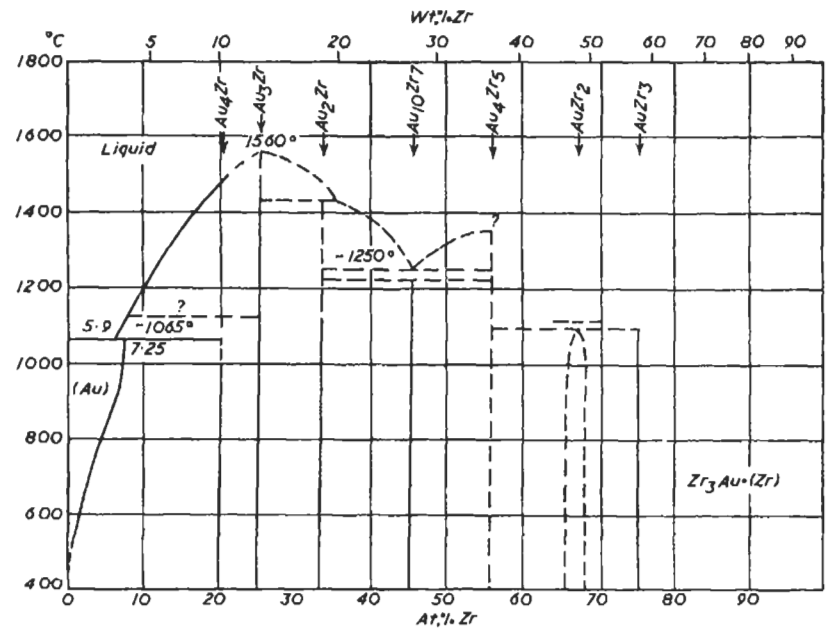
Au–Yb


Wt.% Au
10
20
30
40
50
60
70
80
90
°C
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
Liquid
AuYb
1292°
Au4Yb5
Au2Yb
1240°
Au3Yb
Au4Yb
1150°
Au3Yb7
AuYb2
Au3Yb5
1131°
1063°
1061°
989°
926°
861°
815°
809°
712°
661°
546°
470°
10
20
30
40
50
60
70
80
90
100
At.% Au

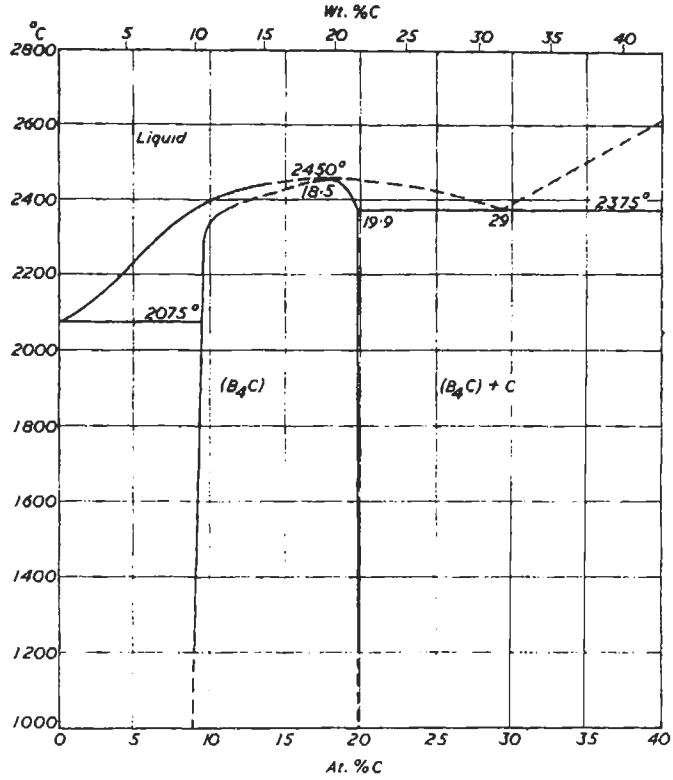
Au–Zn


°C
Wt % Zn
0 10 20 30 40 50 60 70 80 90 100
1100
900
700
500
300
100
-100
1064.43°C
Liquid
751°C
683°
654
585°C
419.58°C
(Au)
β'
520°C
490°C
γ
γ3
438°
(Zn)
420°C
403°C
300°C
α1
270°
300°C
215°
ε
~175°C
180°C
α3
α'2 α2
Au5Zn3
δ
209°C
β1
189°C
γ2
ε'
At % Zn

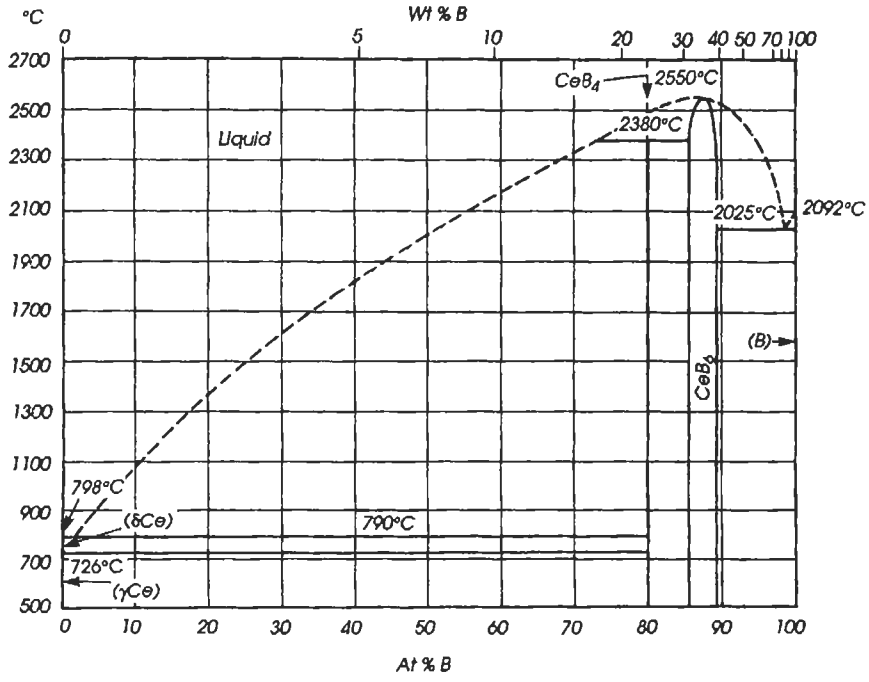
Au–Zr


Wt.% Zr
°C
5 10 20 30 40 50 60 70 80 90
1800
1600
1400
1200
1000
800
600
400
Au4Zr
Au3Zr
Au2Zr
Au10Zr7
Au4Zr5
AuZr2
AuZr3
Liquid
1560°
~1250°
?
5·9
~1065°
7·25
(Au)
Zr3Au•(Zr)
0 10 20 30 40 50 60 70 80 90
At.% Zr

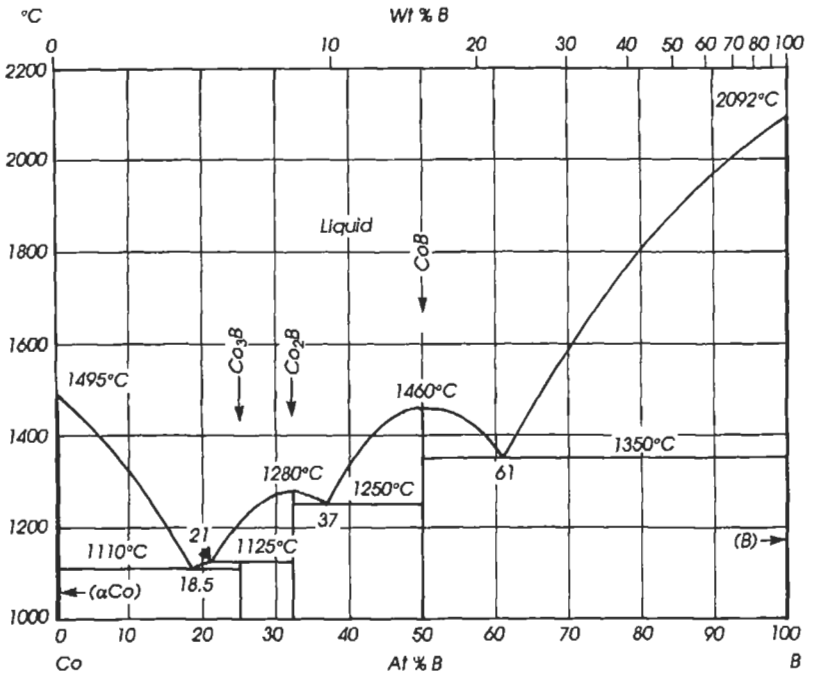
B–C


Wt. %C
°C
5
10
15
20
25
30
35
40
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
Liquid
2450°
18·5
19·9
29
2375°
2075°
(B_4C)
$(B_4C) + C$
0
5
10
15
20
25
30
35
40
At. %C

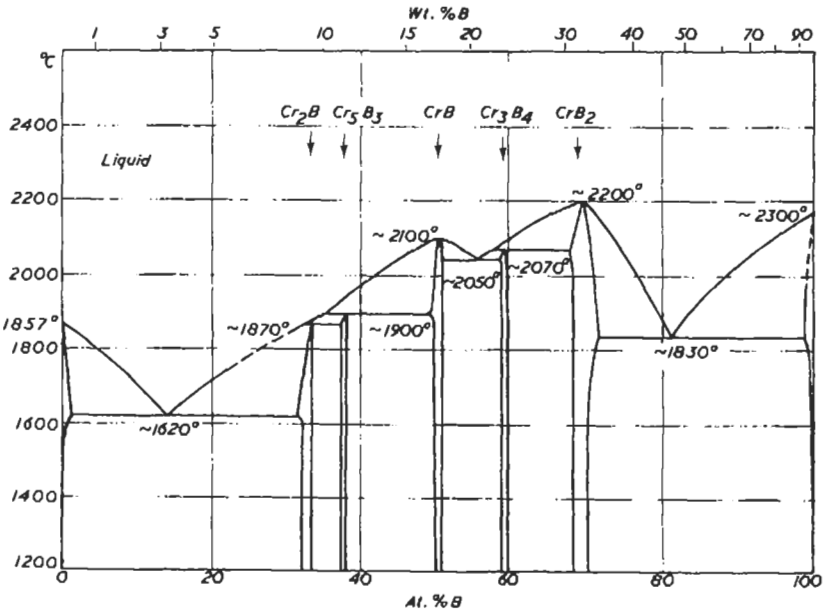
B–Ce


°C
Wt % B
0
5
10
20
30
40
50
70
100
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
CeB_4
2550°C
2380°C
Liquid
2025°C
2092°C
(B)
CeB_6
798°C
(δCe)
790°C
726°C
(γCe)
0
10
20
30
40
50
60
70
80
90
100
At % B

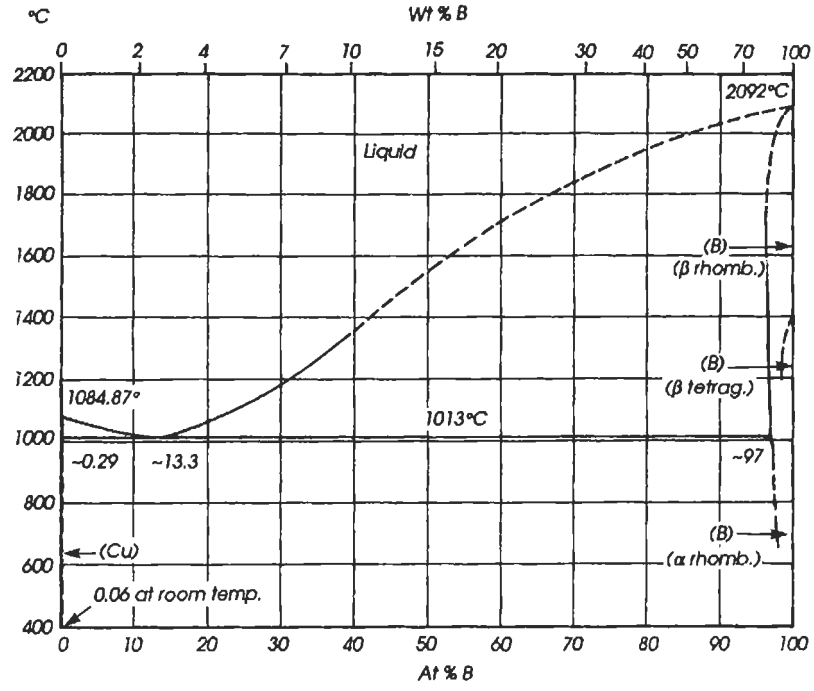
B–Co


°C
Wt % B
0 10 20 30 40 50 60 70 80 100
2200
2000
1800
1600
1400
1200
1000
2092°C
Liquid
Co3B
Co2B
CoB
1495°C
1460°C
1350°C
1280°C
1250°C
61
37
21
1110°C
1125°C
18.5
(αCo)
(B)
0 10 20 30 40 50 60 70 80 90 100
Co
At % B
B

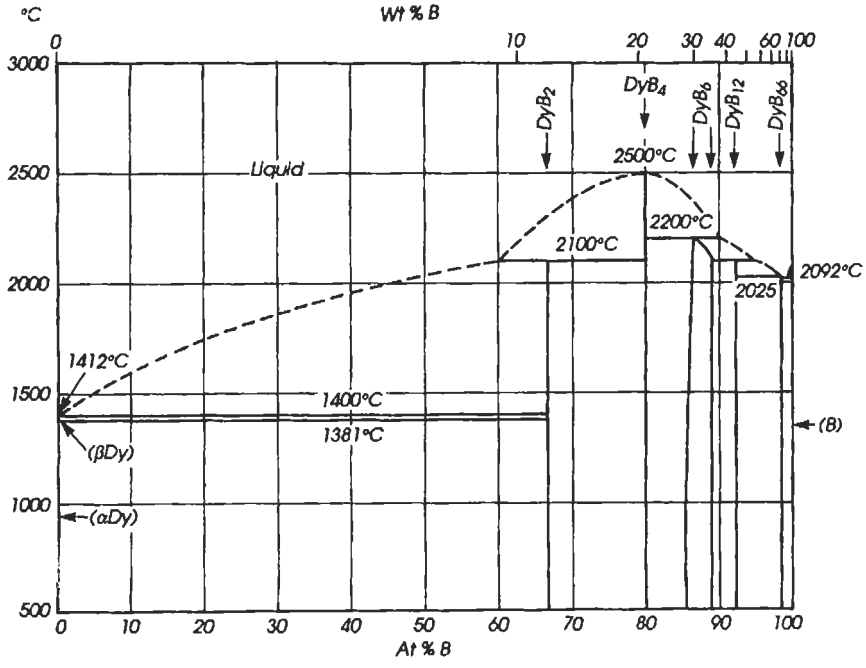
B–Cr


Wt. % B
1 3 5 10 15 20 30 40 50 70 90
°C
Cr2B Cr5B3 CrB Cr3B4 CrB2
2400
Liquid
2200
2000
1857°
1800
1600
1400
1200
~2200°
~2300°
~2100°
~2070°
~2050°
~1870°
~1900°
~1830°
~1620°
0 20 40 60 80 100
At. % B

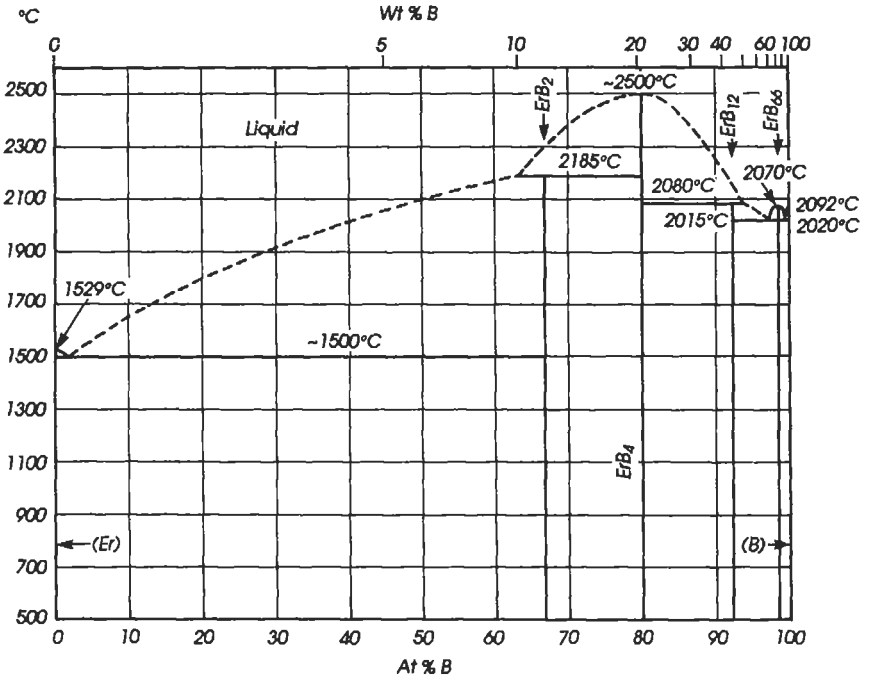
B–Cu


°C
Wt % B
0 2 4 7 10 15 20 30 40 50 70 100
2200
2000
1800
1600
1400
1200
1000
800
600
400
Liquid
2092°C
(B)
(β rhomb.)
(B)
(β tetrag.)
1084.87°
1013°C
~0.29
~13.3
~97
(B)
(α rhomb.)
(Cu)
0.06 at room temp.
0 10 20 30 40 50 60 70 80 90 100
At % B

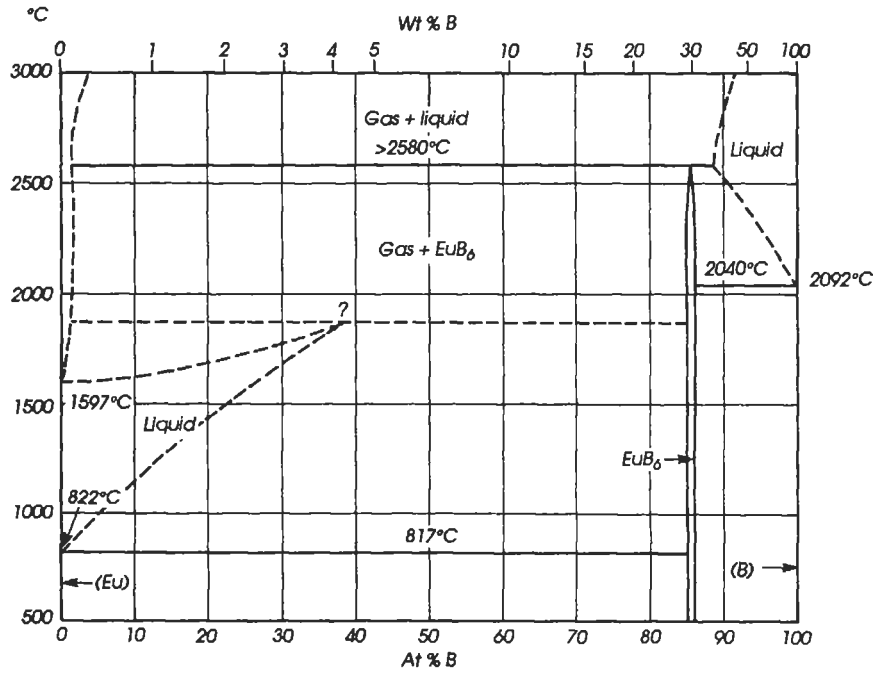
B–Dy


°C
Wt % B
0 10 20 30 40 60 100
3000
2500
2000
1500
1000
500
DyB2
DyB4
DyB6
DyB12
DyB66
2500°C
Liquid
2200°C
2100°C
2092°C
2025
1412°C
1400°C
1381°C
(B)
(βDy)
(αDy)
0 10 20 30 40 50 60 70 80 90 100
At % B

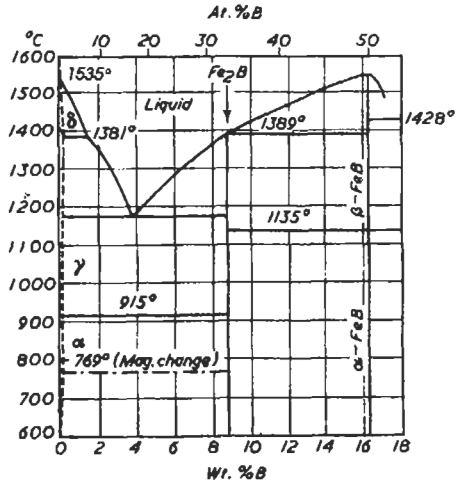
B–Er


°C
Wt % B
0
5
10
20
30
40
60
100
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
Liquid
~2500°C
ErB2
ErB12
ErB66
2185°C
2080°C
2070°C
2092°C
2020°C
2015°C
1529°C
~1500°C
ErB4
(Er)
(B)
0
10
20
30
40
50
60
70
80
90
100
At % B

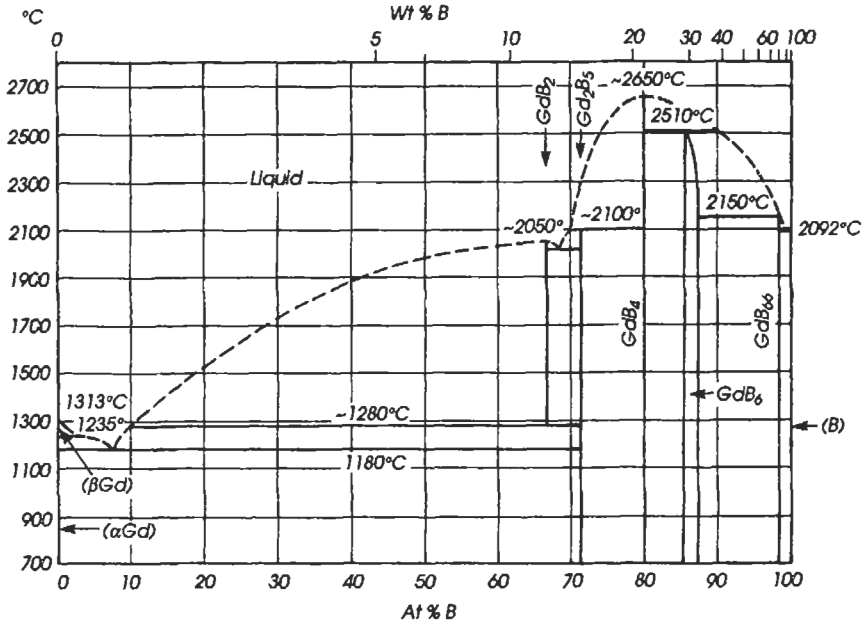
B–Eu


°C
Wt % B
0
1
2
3
4
5
10
15
20
30
50
100
3000
2500
2000
1500
1000
500
Gas + liquid
>2580°C
Liquid
Gas + EuB6
2040°C
2092°C
?
1597°C
Liquid
EuB6
822°C
817°C
(Eu)
(B)
0
10
20
30
40
50
60
70
80
90
100
At % B

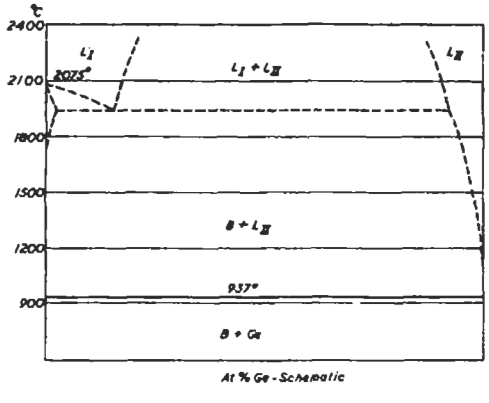
B–Fe


At.%B
°C
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
10
20
30
40
50
1535°
Fe2B
Liquid
δ
1381°
1389°
1428°
β-FeB
1135°
γ
915°
α-FeB
α
769° (Mag. change)
0
2
4
6
8
10
12
14
16
18
Wt. %B

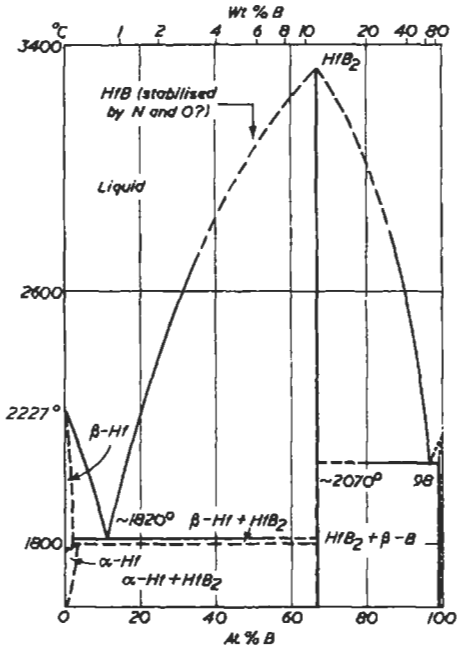
B–Gd


°C
Wt % B
0
5
10
20
30
40
60
100
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
700
GdB2
Gd2B5
~2650°C
2510°C
Liquid
~2100°
2150°C
~2050°
2092°C
GdB4
GdB66
GdB6
(B)
1313°C
1235°
~1280°C
1180°C
(βGd)
(αGd)
0
10
20
30
40
50
60
70
80
90
100
At % B

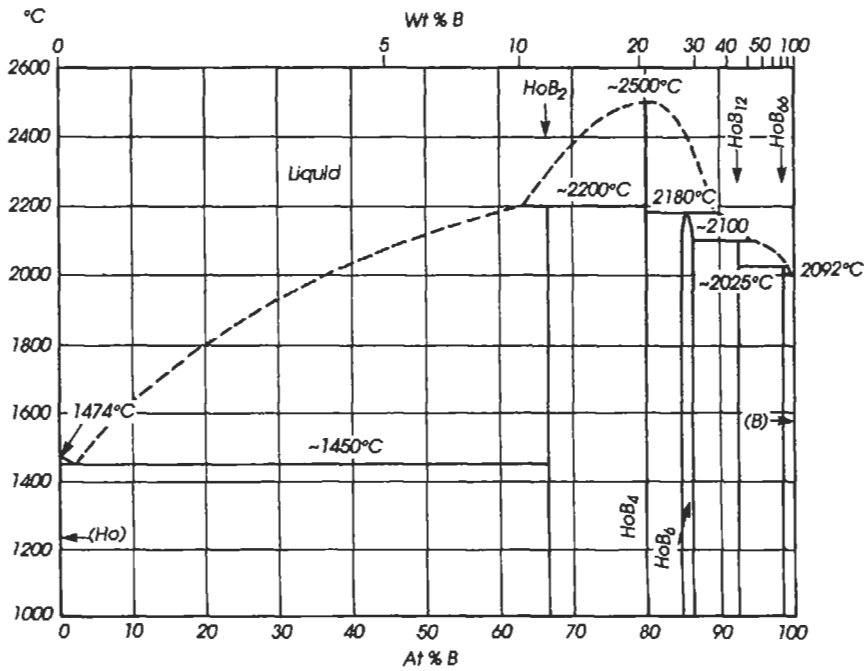
B–Ge


°C
2400
2100
1800
1500
1200
900
L1
2075°
L1 + LII
LII
B + LII
937°
B + Ge
At % Ge - Schematic

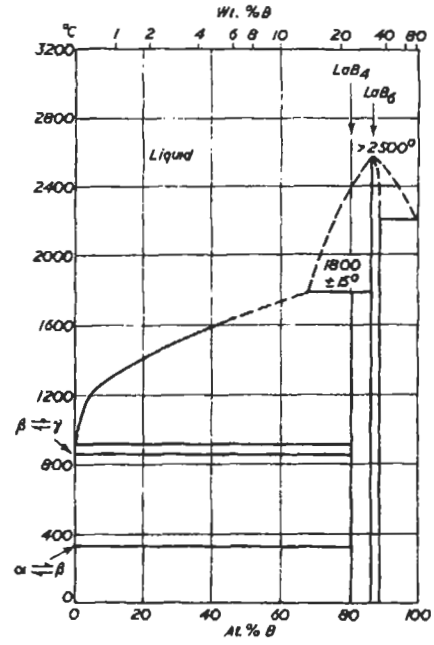
B–Hf


Wt % B
°C
1
2
4
6
8
10
20
40
80
3400
2600
2227°
1800
HfB (stabilised by N and O?)
HfB2
Liquid
β-Hf
~1820°
β-Hf + HfB2
~2070°
98
HfB2 + β-B
α-Hf
α-Hf + HfB2
0
20
40
60
80
100
At % B

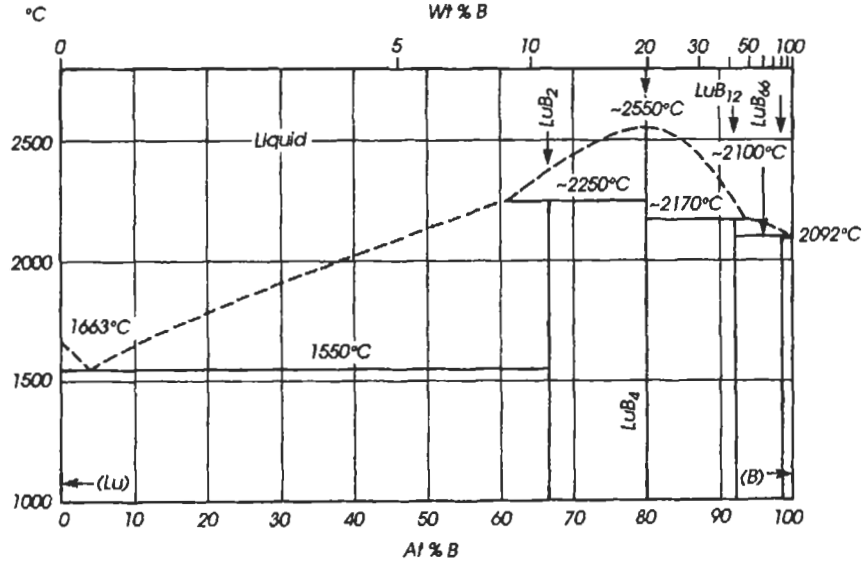
B–Ho


°C
Wt % B
0
5
10
20
30
40
50
100
2600
2400
2200
2000
1800
1600
1400
1200
1000
HoB2
~2500°C
HoB12
HoB66
Liquid
~2200°C
2180°C
~2100
2092°C
~2025°C
1474°C
~1450°C
(B)
(Ho)
HoB4
HoB6
0
10
20
30
40
50
60
70
80
90
100
At % B

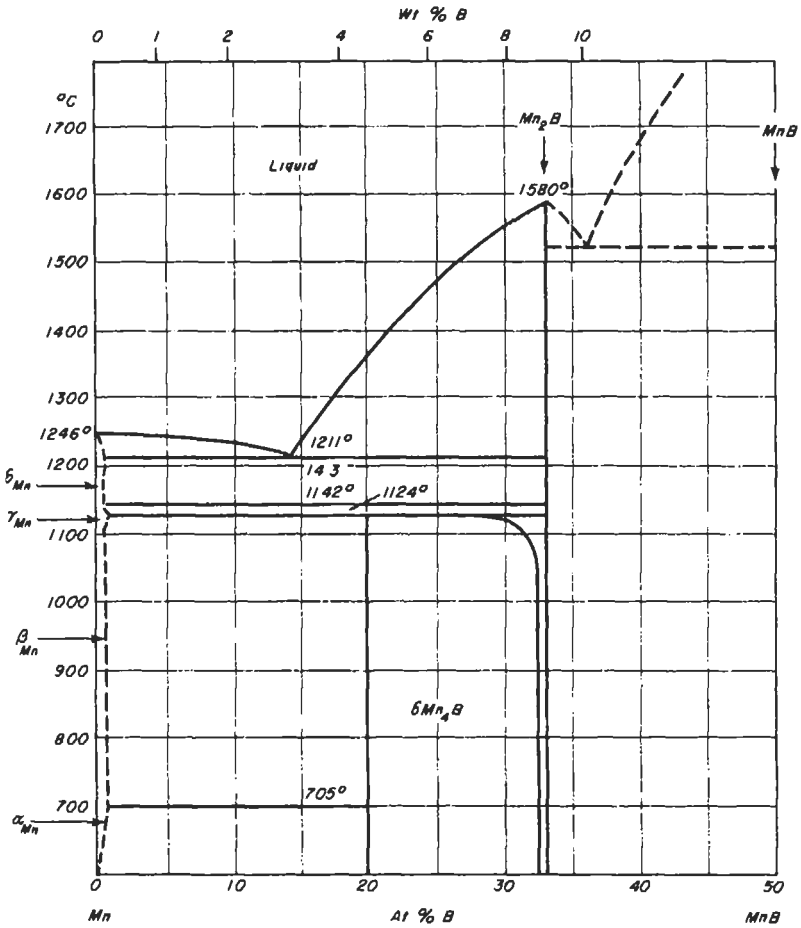
B–La


Wt. % B
°C
1
2
4
6
8
10
20
40
80
3200
2800
2400
2000
1600
1200
800
400
0
LaB4
LaB6
Liquid
>2500°
1800
±15°
β ⇌ γ
α ⇌ β
0
20
40
60
80
100
At % B

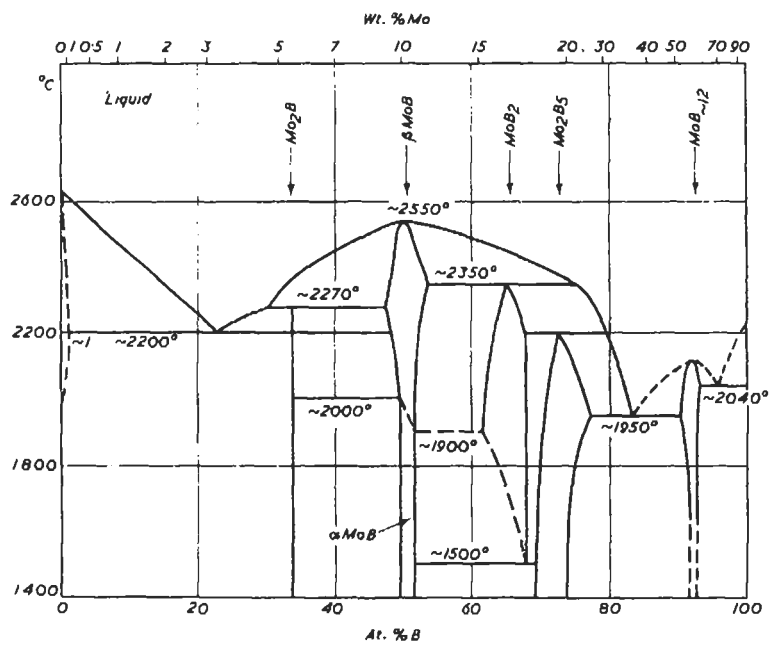
B–Lu


°C
Wt % B
0
5
10
20
30
50
100
LuB2
~2550°C
LuB12
LuB66
2500
Liquid
~2100°C
~2250°C
~2170°C
2092°C
2000
1663°C
1550°C
1500
LuB4
(Lu)
(B)
1000
0
10
20
30
40
50
60
70
80
90
100
At % B

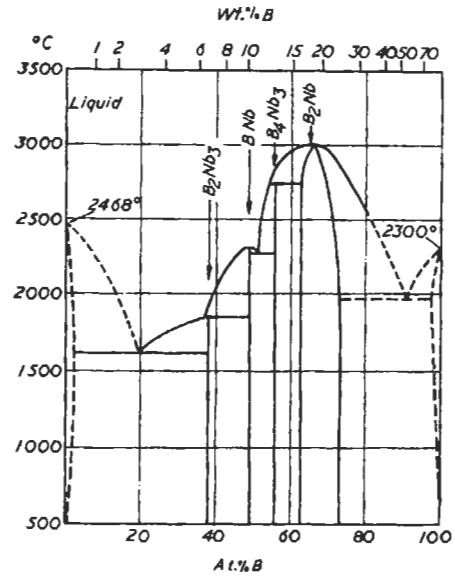
B–Mn


Wt % B
0
1
2
4
6
8
10
°C
1700
1600
1500
1400
1300
1246°
1200
1100
1000
900
800
700
δMn
γMn
βMn
αMn
Liquid
Mn2B
MnB
1580°
1211°
143
1142°
1124°
δMn4B
705°
0
10
20
30
40
50
Mn
At % B
MnB

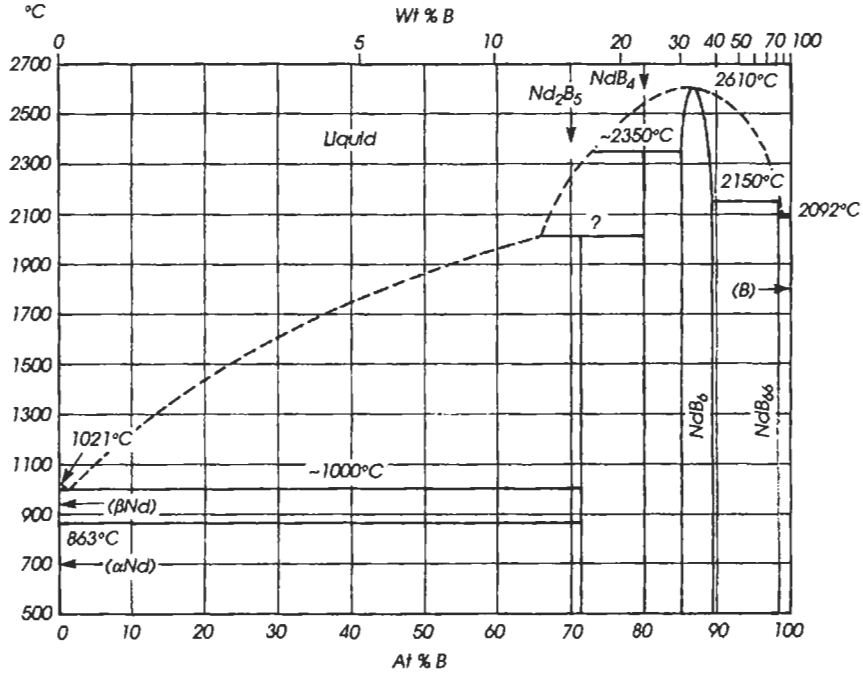
B–Mo


Wt. %Mo
0 0·5 1
2
3
5
7
10
15
20
30
40
50
70
90
°C
Liquid
Mo2B
βMoB
MoB2
Mo2B5
MoB~12
2600
2200
1800
1400
~2550°
~2350°
~2270°
~1
~2200°
~2000°
~1900°
~1950°
~2040°
αMoB
~1500°
0
20
40
60
80
100
At. %B

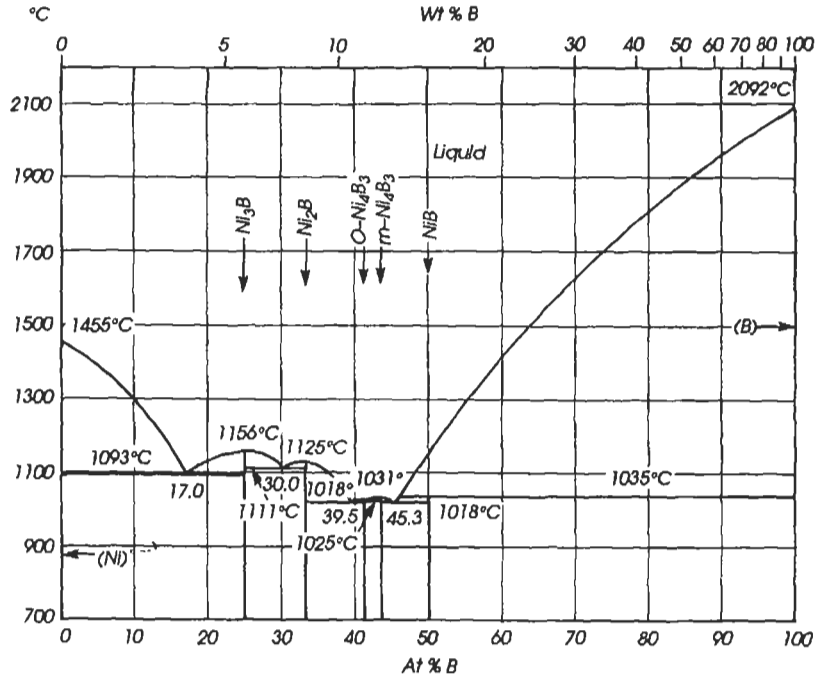
B–Nb


Wt.% B
°C
1 2 4 6 8 10 15 20 30 40 50 70
3500
3000
2500
2000
1500
1000
500
Liquid
2468°
B Nb
B2Nb3
B4Nb3
B2Nb
2300°
20 40 60 80 100
At.% B

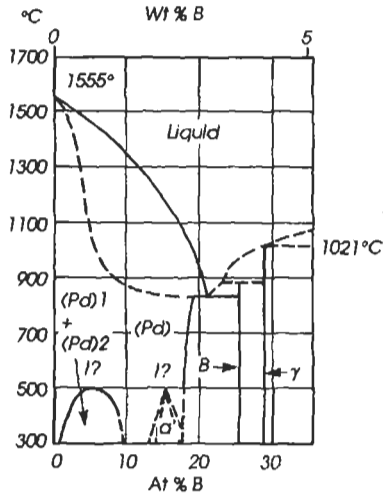
B–Nd


°C
Wt % B
0 5 10 20 30 40 50 70 100
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
Liquid
Nd2B5
NdB4
2610°C
~2350°C
2150°C
2092°C
?
(B)
NdB6
NdB66
1021°C
~1000°C
(βNd)
863°C
(αNd)
0 10 20 30 40 50 60 70 80 90 100
At % B

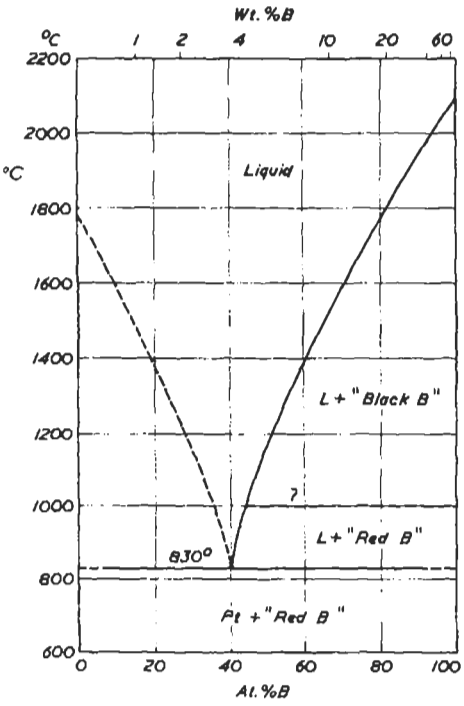
B–Ni


°C
Wt % B
0 5 10 20 30 40 50 60 70 80 100
2100
1900
1700
1500
1300
1100
900
700
2092°C
Liquid
Ni3B
Ni2B
O-Ni4B3
m-Ni4B3
NiB
1455°C
(B)
1156°C
1125°C
1093°C
1031°
1035°C
17.0
30.0
1018°
1111°C
39.5
45.3
1018°C
1025°C
(Ni)
0 10 20 30 40 50 60 70 80 90 100
At % B

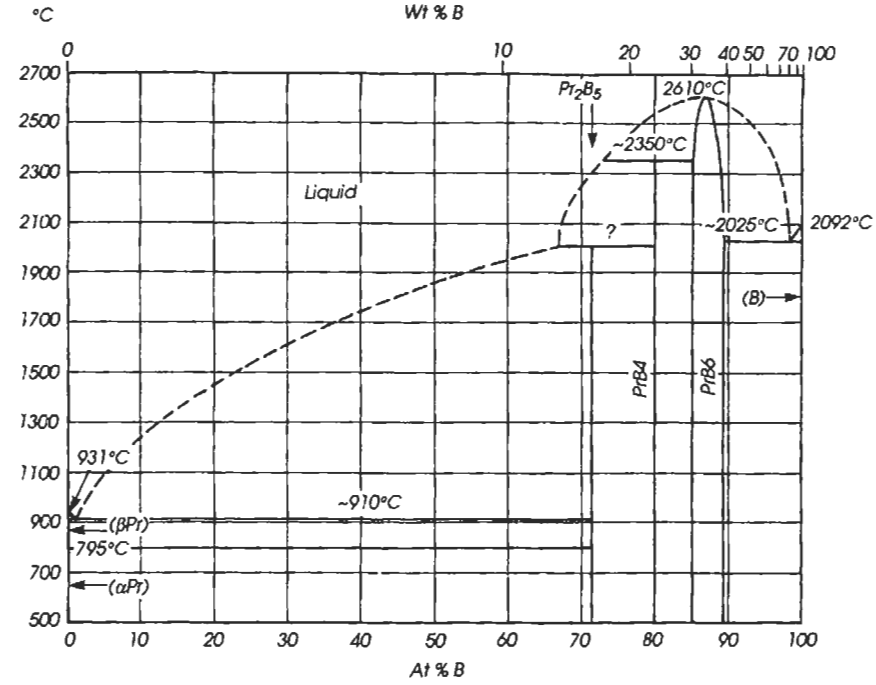
B–Pd


°C
Wt % B
0 5
1700
1500
1300
1100
900
700
500
300
1555°
Liquid
1021°C
(Pd)1
+
(Pd)2
(Pd)
B
γ
α
0 10 20 30
At % B

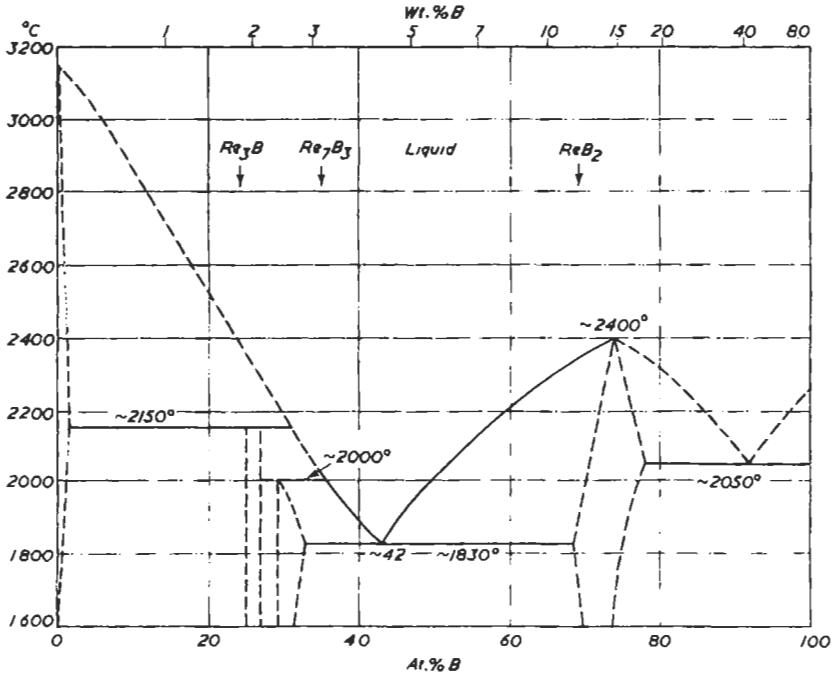
B–Pt


Wt. %B
°C
1 2 4 10 20 60
2200
2000
1800
1600
1400
1200
1000
800
600
Liquid
L + "Black B"
?
L + "Red B"
830°
Pt + "Red B"
0 20 40 60 80 100
At. %B

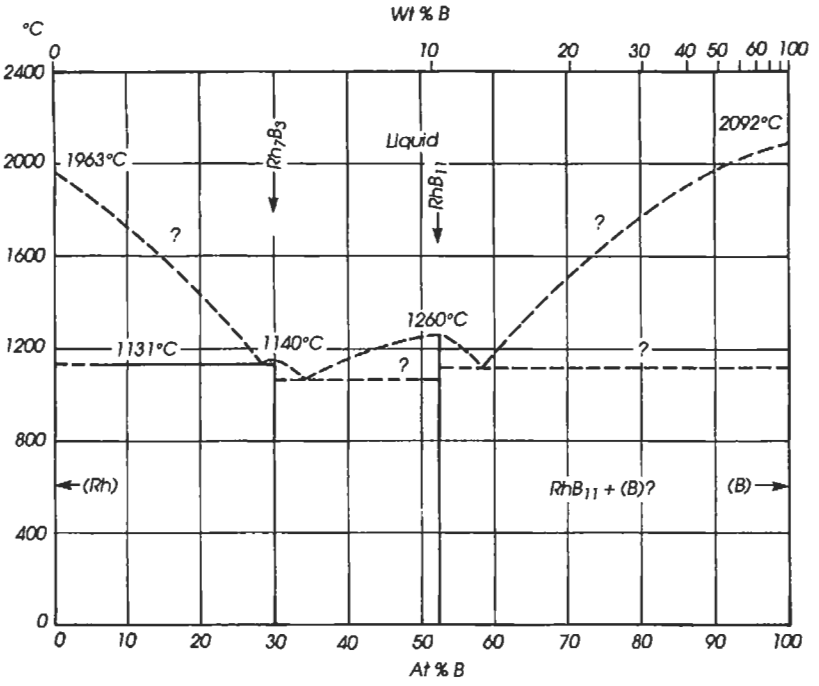
B–Pr


°C
Wt % B
0
10
20
30
40 50
70 100
2700
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
Pr_2B_5
2610°C
~2350°C
Liquid
?
~2025°C
2092°C
(B)
PrB4
PrB6
931°C
~910°C
(βPr)
795°C
(αPr)
0 10 20 30 40 50 60 70 80 90 100
At % B

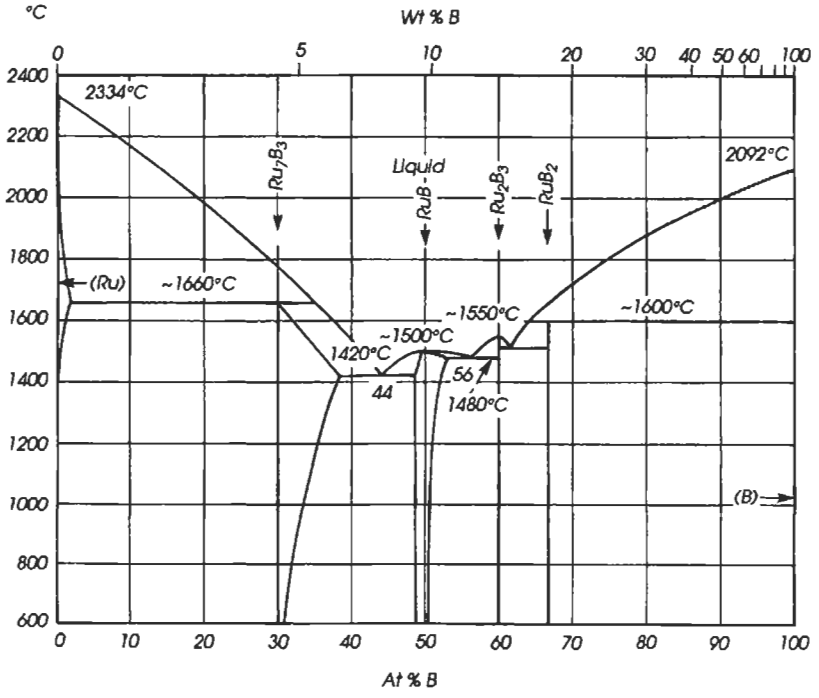
B–Re


Wt. % B
°C
1
2
3
5
7
10
15
20
40
80
3200
3000
2800
2600
2400
2200
2000
1800
1600
Re_3B
Re_7B_3
Liquid
ReB_2
~2400°
~2150°
~2000°
~2050°
~42
~1830°
0 20 40 60 80 100
At. % B

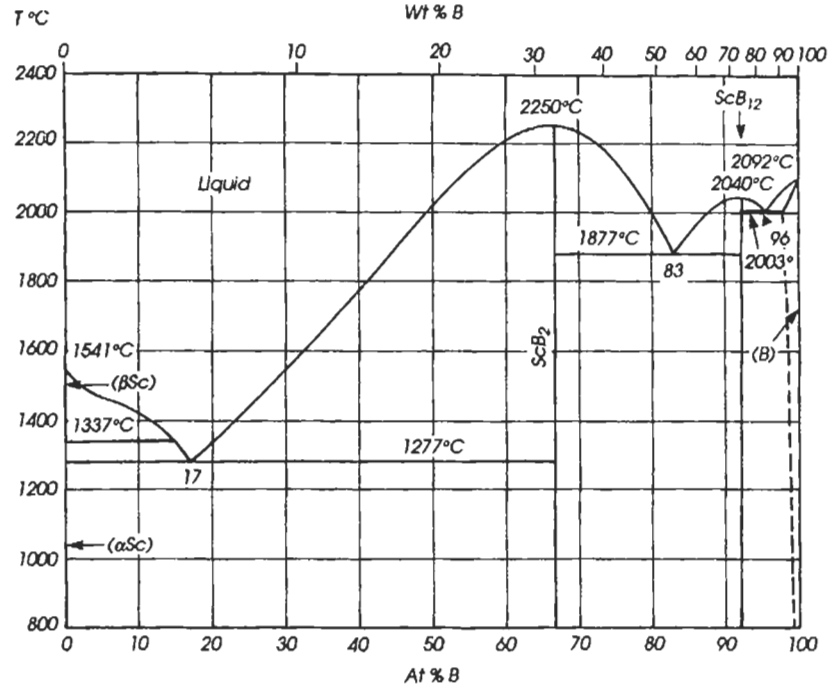
B–Rh


°C
Wt % B
0
10
20
30
40
50
60
100
2400
2000
1600
1200
800
400
0
1963°C
Rh7B3
Liquid
RhB11
2092°C
?
?
1131°C
1140°C
1260°C
?
?
(Rh)
RhB11 + (B)?
(B)
0
10
20
30
40
50
60
70
80
90
100
At % B

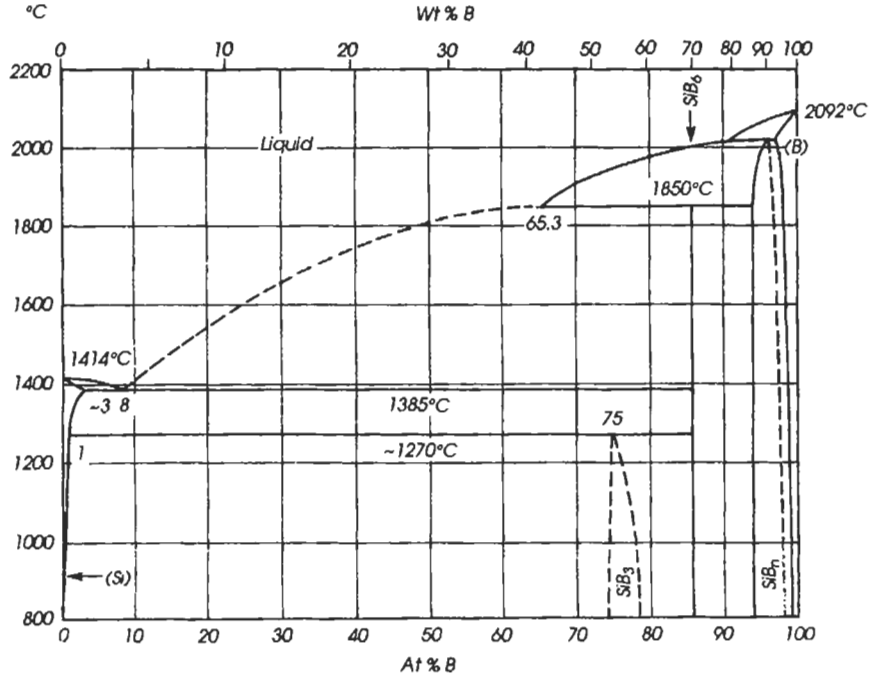
B–Ru


°C
Wt % B
0
5
10
20
30
40
50
60
100
2400
2200
2000
1800
1600
1400
1200
1000
800
600
2334°C
Ru7B3
Liquid
RuB
Ru2B3
RuB2
2092°C
(Ru)
~1660°C
~1550°C
~1600°C
~1500°C
1420°C
44
56
1480°C
(B)
0
10
20
30
40
50
60
70
80
90
100
At % B

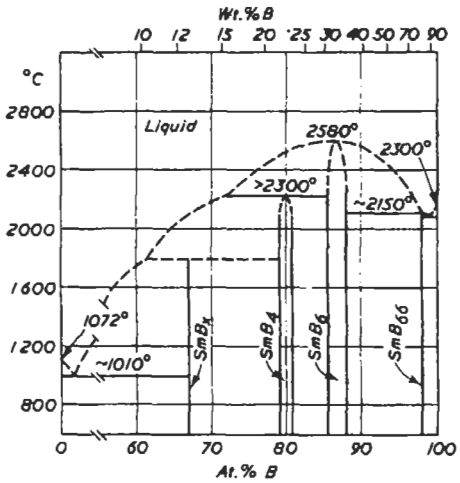
B–Sc


T °C
Wt % B
0 10 20 30 40 50 60 70 80 90 100
2400
2200
2000
1800
1600
1400
1200
1000
800
Liquid
2250°C
ScB12
2092°C
2040°C
1877°C
96
2003°
83
1541°C
(βSc)
1337°C
17
1277°C
ScB2
(B)
(αSc)
0 10 20 30 40 50 60 70 80 90 100
At % B

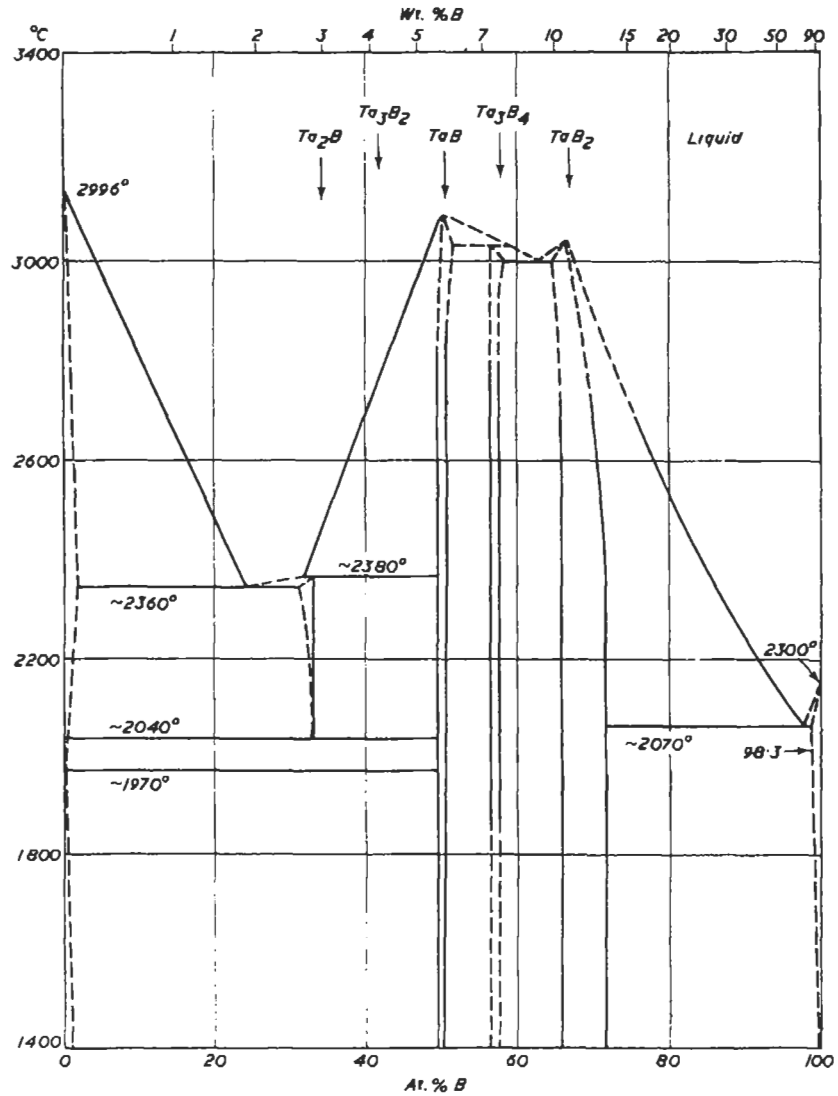
B–Si


°C
Wt % B
0 10 20 30 40 50 60 70 80 90 100
2200
2000
1800
1600
1400
1200
1000
800
SiB6
2092°C
Liquid
(B)
1850°C
65.3
1414°C
~3 8
1385°C
75
1
~1270°C
(Si)
SiB3
SiBn
0 10 20 30 40 50 60 70 80 90 100
At % B

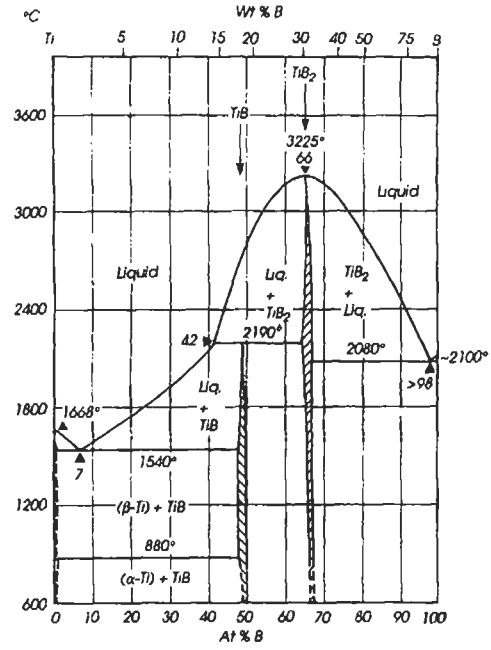
B–Sm


Wt.% B
10 12 15 20 25 30 40 50 70 90
°C
2800
2400
2000
1600
1200
800
Liquid
2580°
2300°
>2300°
~2150°
1072°
~1010°
SmB$_x$
SmB$_4$
SmB$_6$
SmB$_{66}$
0 60 70 80 90 100
At.% B

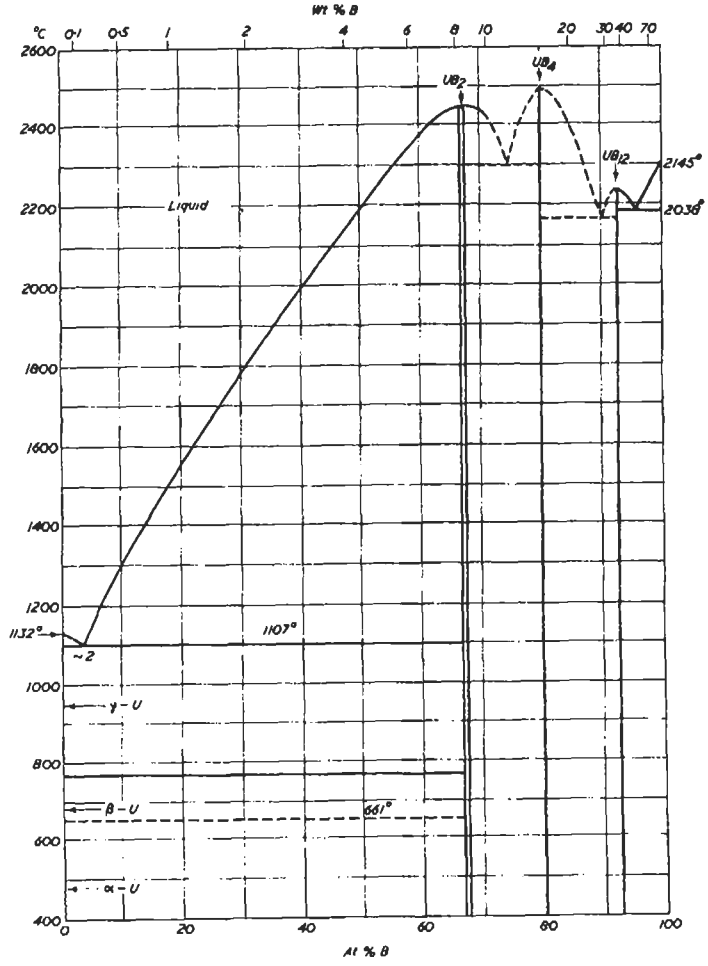
B–Ta


Wt. % B
°C
1 2 3 4 5 7 10 15 20 30 50 90
3400
3000
2600
2200
1800
1400
Ta$_2$B
Ta$_3$B$_2$
TaB
Ta$_3$B$_4$
TaB$_2$
Liquid
2996°
~2380°
~2360°
~2040°
~1970°
2300°
~2070°
98·3
0 20 40 60 80 100
At.% B

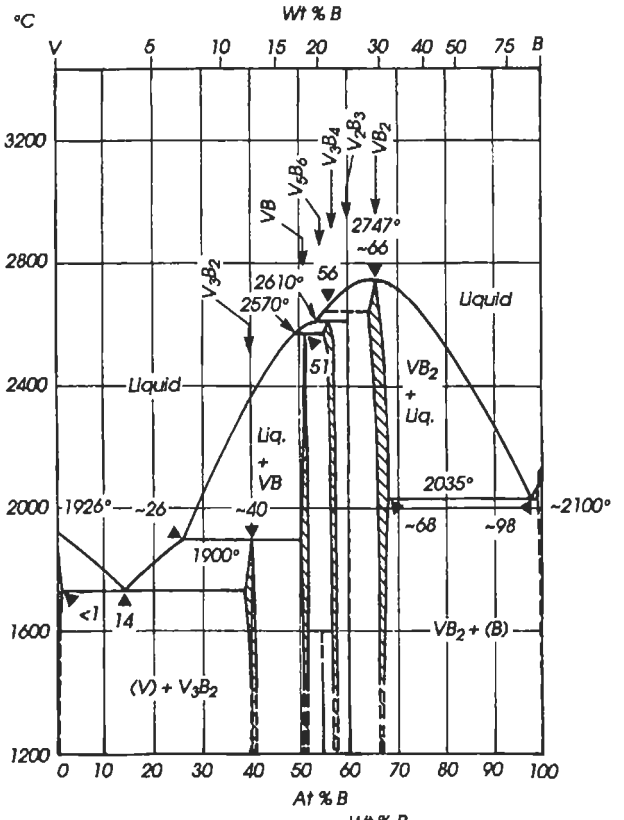
B–Ti


°C
Wt % B
Ti
5
10
15
20
30
40
50
75
B
TiB_2
TiB
3225°
66
Liquid
3600
3000
2400
1800
1200
600
Liquid
Liq. + TiB_2
TiB_2 + Liq.
42
2190°
2080°
~2100°
>98
Liq. + TiB
1668°
7
1540°
(β-Ti) + TiB
880°
(α-Ti) + TiB
0 10 20 30 40 50 60 70 80 90 100
At % B

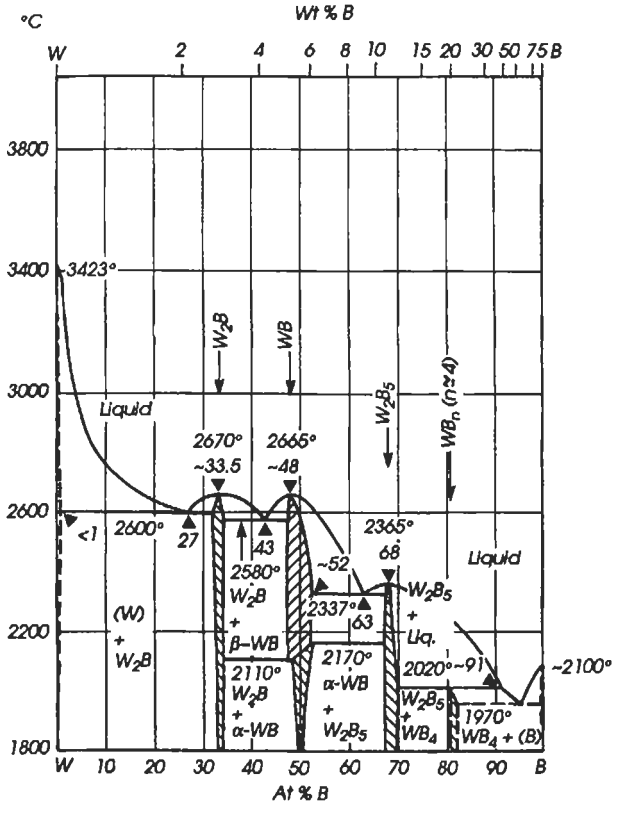
B–U


Wt % B
°C
0·1
0·5
1
2
4
6
8
10
20
30
40
70
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
UB_2
UB_4
UB_{12}
2145°
2036°
Liquid
1132°
1107°
~2
γ – U
β – U
661°
α – U
0 20 40 60 80 100
At % B

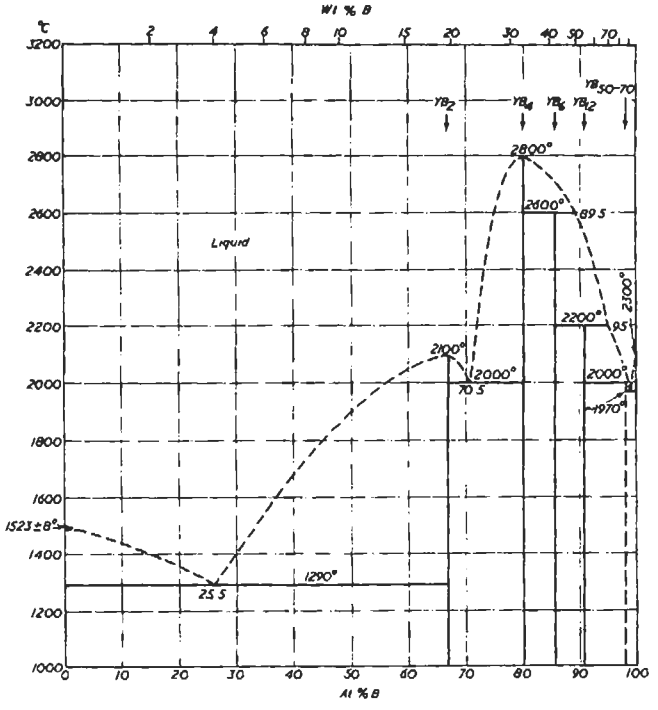
B–V


°C
Wt % B
V 5 10 15 20 30 40 50 75 B
3200
2800
2400
2000
1600
1200
VB
V_5B_6
V_3B_4
V_2B_3
VB_2
2747°
~66
V_3B_2
2610°
2570°
56
51
Liquid
Liquid
VB_2 + Liq.
Liq. + VB
1926°
~26
~40
1900°
2035°
~68
~98
~2100°
<1
14
VB_2 + (B)
(V) + V_3B_2
0 10 20 30 40 50 60 70 80 90 100
At % B

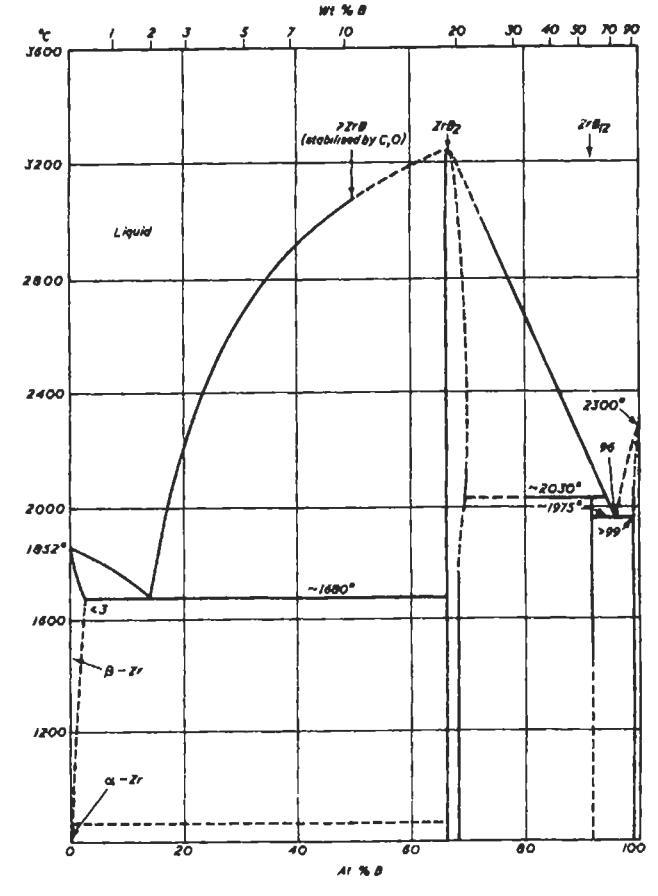
B–W


°C
Wt % B
W 2 4 6 8 10 15 20 30 50 75 B
3800
3400
3000
2600
2200
1800
3423°
W_2B
WB
W_2B_5
WB_n (n≈4)
Liquid
2670°
~33.5
2666°
~48
<1
2600°
27
43
2580°
W_2B + β–WB
(W) + W_2B
2110°
W_2B + α–WB
~52
2337°
63
2365°
68
Liquid
W_2B_5 + Liq.
2170°
α–WB + W_2B_5
2020°
~91
~2100°
W_2B_5 + WB_4
1970°
WB_4 + (B)
W 10 20 30 40 50 60 70 80 90 B
At % B

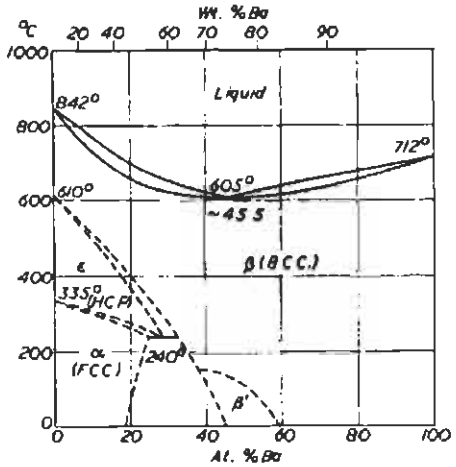
B–Y


Wt % B
°C
Liquid
YB2
YB4
YB6
YB12
YB50-70
2800°
2600°
89 S
2300°
2200°
95
2100°
2000°
~1970°
1523±8°
25 S
1290°
70 S
At % B

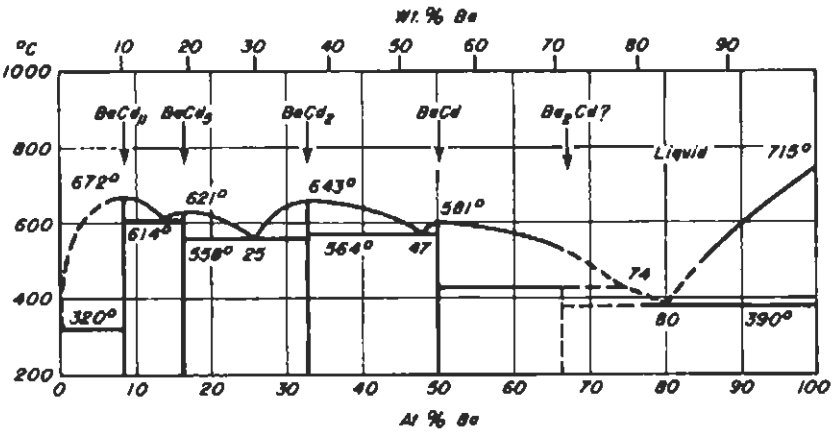
B–Zr


Wt % B
°C
Liquid
~ZrB
(stabilised by C,O)
ZrB2
ZrB12
2300°
96
~2030°
~1975°
>99
1852°
~1680°
<3
β – Zr
α – Zr
At % B

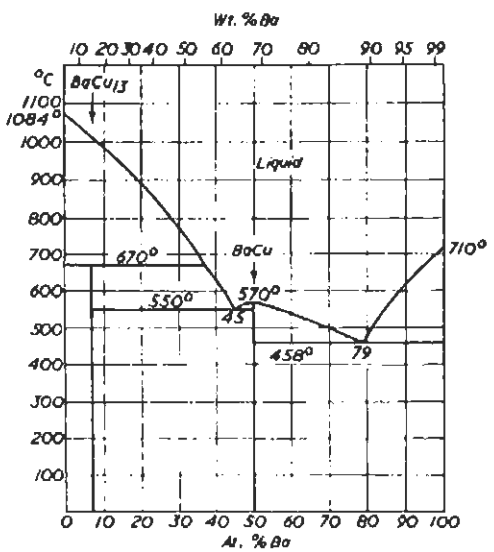
Ba–Ca



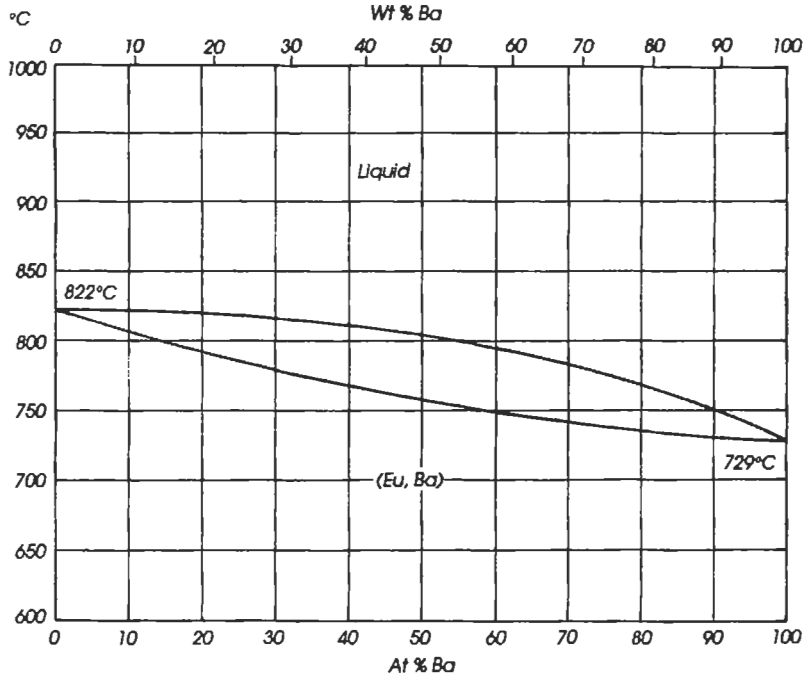
Ba–Cd



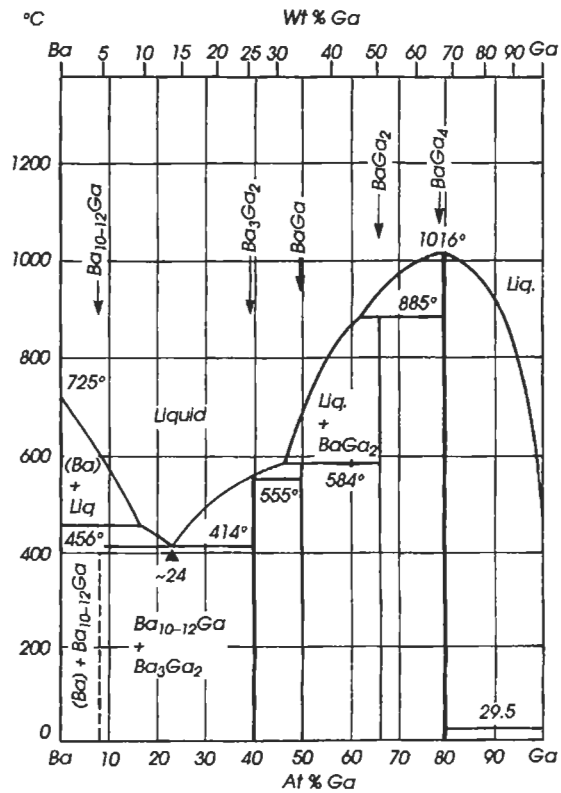
Ba–Cu



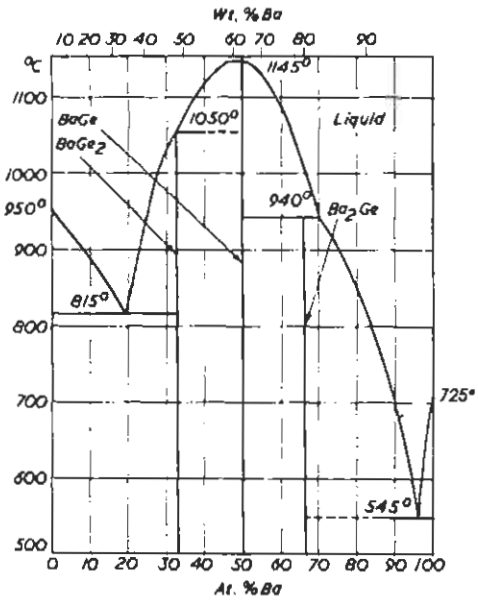
Ba–Eu


°C
Wt % Ba
0 10 20 30 40 50 60 70 80 90 100
1000
950
900
850
800
750
700
650
600
Liquid
822°C
729°C
(Eu, Ba)
0 10 20 30 40 50 60 70 80 90 100
At % Ba

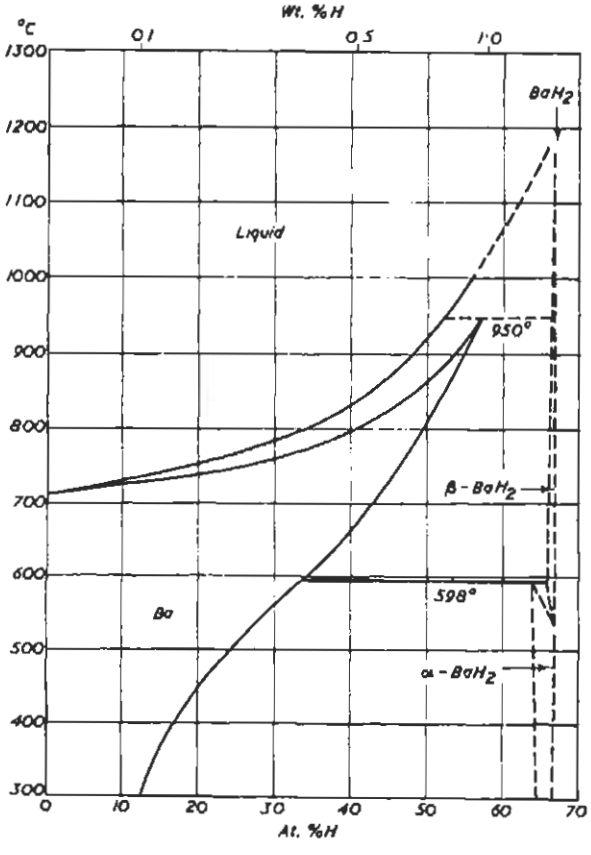
Ba–Ga


°C
Wt % Ga
Ba 5 10 15 20 25 30 40 50 60 70 80 90 Ga
1200
1000
800
600
400
200
0
$Ba_{10-12}Ga$
Ba_3Ga_2
BaGa
$BaGa_2$
$BaGa_4$
1016°
885°
Liq.
725°
Liquid
Liq. + $BaGa_2$
(Ba) + Liq
584°
555°
456°
414°
~24
$Ba_{10-12}Ga$ + Ba_3Ga_2
(Ba) + $Ba_{10-12}Ga$
29.5
Ba 10 20 30 40 50 60 70 80 90 Ga
At % Ga

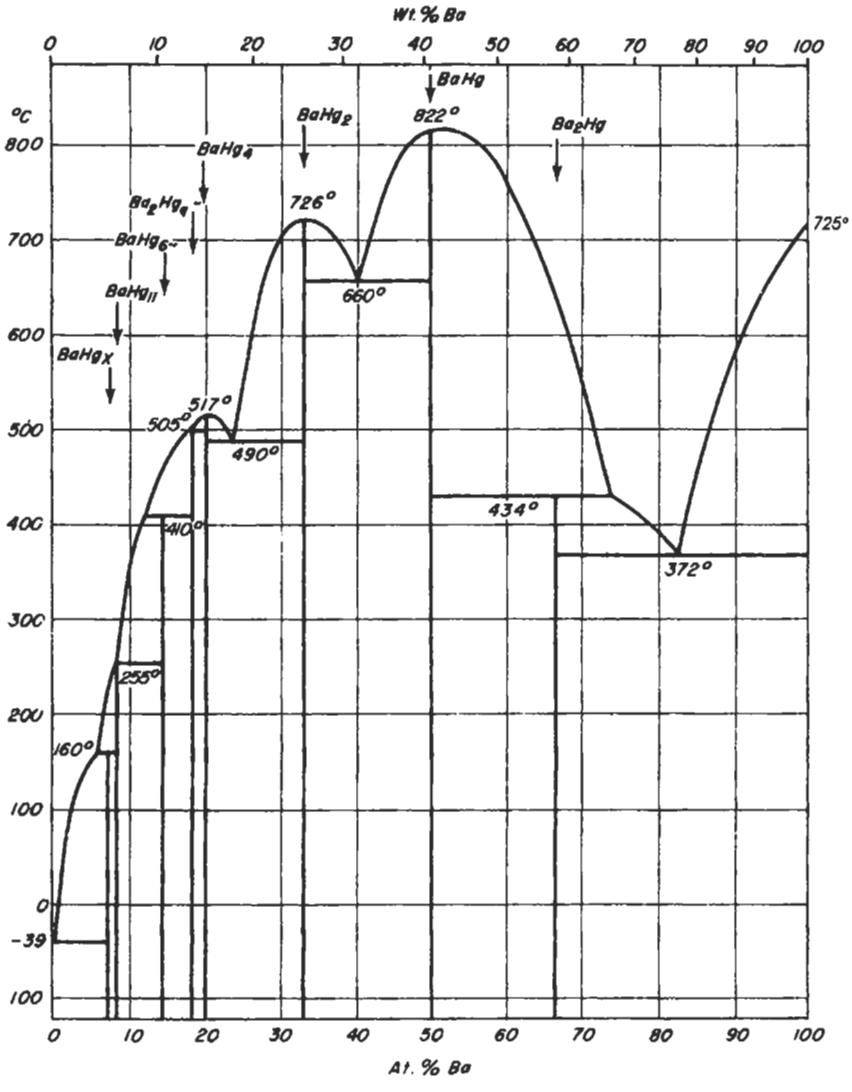
Ba–Ge


Wt. % Ba
10 20 30 40 50 60 70 80 90
°C
1100
1000
950°
900
800
700
600
500
1145°
1050°
940°
815°
545°
725°
BaGe
BaGe2
Liquid
Ba2Ge
0 10 20 30 40 50 60 70 80 90 100
At. % Ba

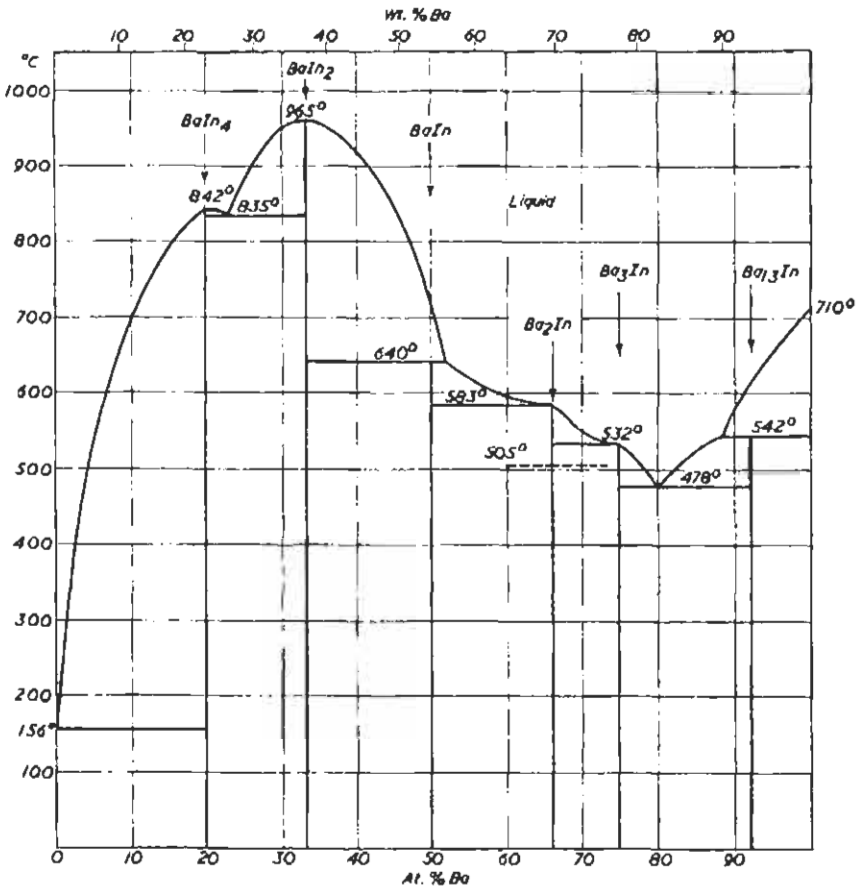
Ba–H


Wt. % H
°C
0·1
0·5
1·0
1300
1200
1100
1000
900
800
700
600
500
400
300
BaH2
Liquid
950°
β - BaH2
598°
Ba
α - BaH2
0 10 20 30 40 50 60 70
At. % H

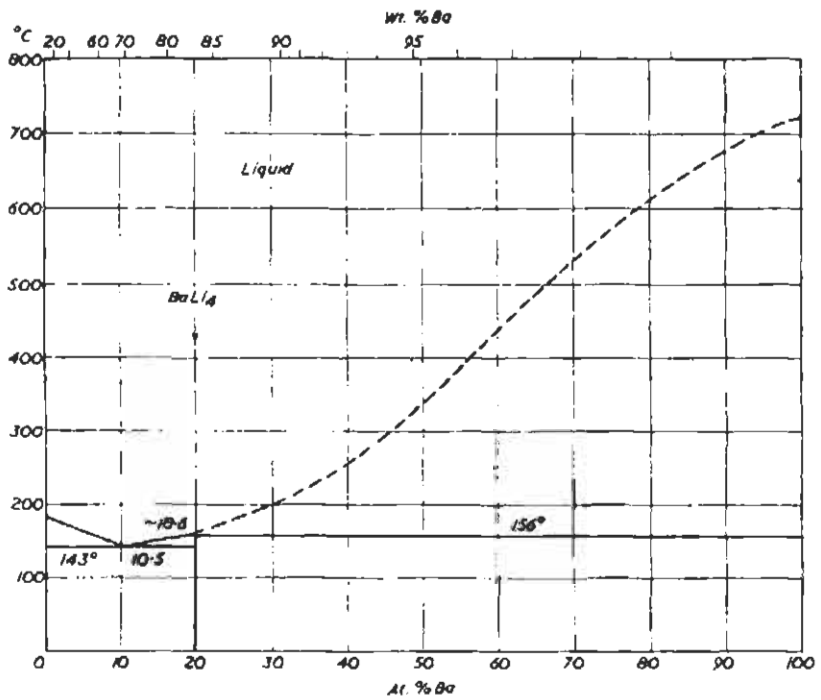
Ba–Hg


Wt. % Ba
0
10
20
30
40
50
60
70
80
90
100
°C
800
700
600
500
400
300
200
100
0
-39
100
BaHg
822°
BaHg2
726°
BaHg4
Ba2Hg5
BaHg6
BaHg11
BaHgX
660°
725°
517°
505°
490°
434°
410°
372°
255°
160°
At. % Ba

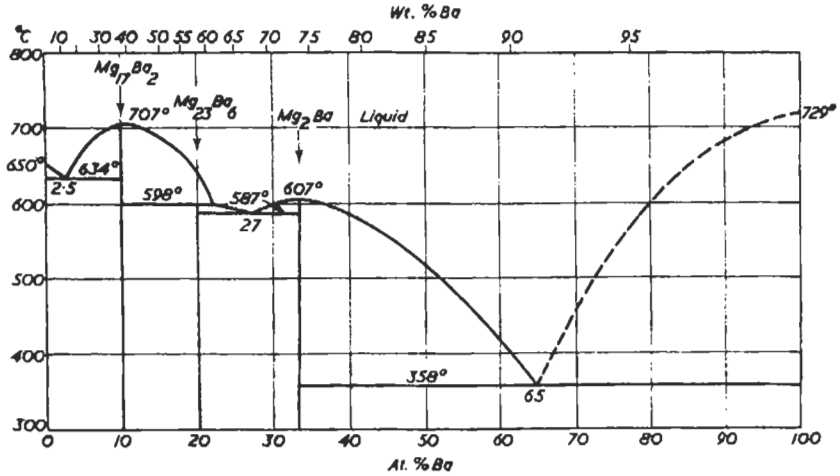
Ba–In


Wt. % Ba
°C
BaIn2
965°
BaIn4
BaIn
842°
835°
Liquid
Ba3In
Ba13In
710°
Ba2In
640°
593°
532°
542°
505°
478°
156°
At. % Ba

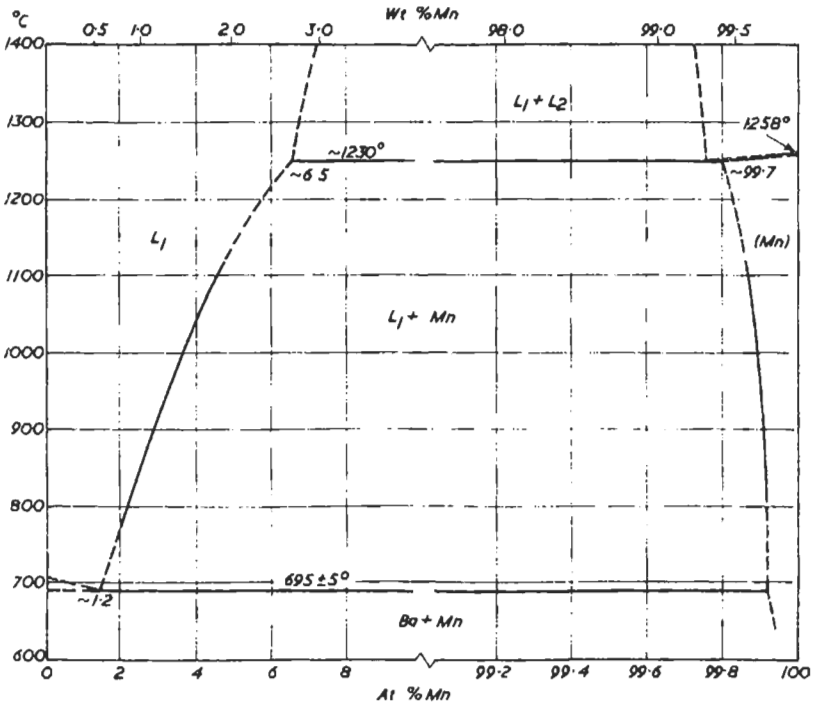
Ba–Li


Wt. % Ba
°C
Liquid
BaLi4
~18·8
156°
143°
10·5
At. % Ba

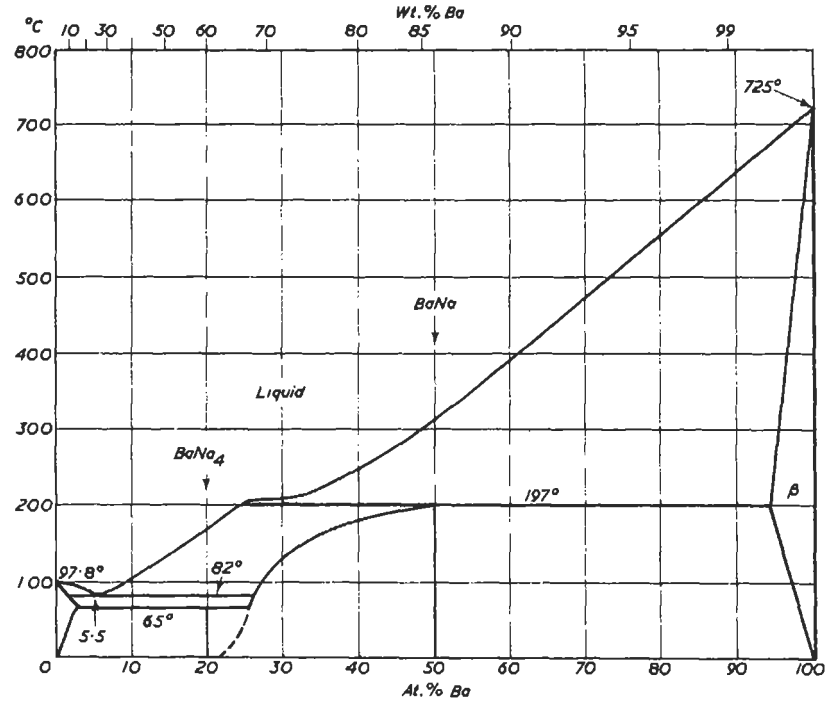
Ba–Mg


Wt. % Ba
°C
$Mg_{17}Ba_2$
$Mg_{23}Ba_6$
Mg_2Ba
Liquid
707°
634°
2·5
598°
587°
27
607°
358°
65
729°
At. % Ba

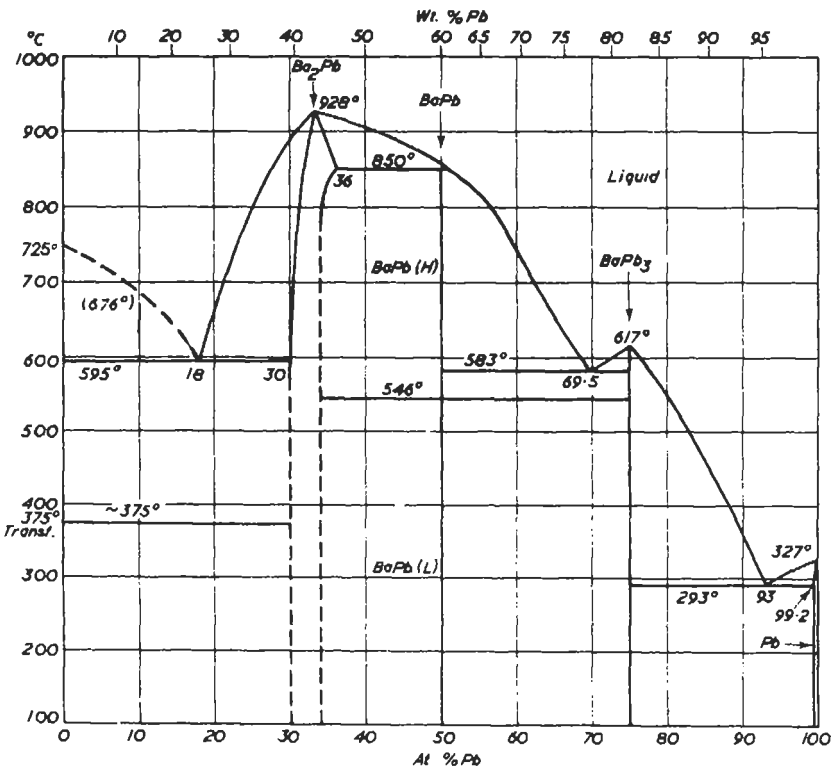
Ba–Mn


°C
Wt % Mn
$L_1 + L_2$
~1230°
~6·5
1258°
~99·7
L_1
(Mn)
L_1 + Mn
695 ± 5°
~1·2
Ba + Mn
At % Mn

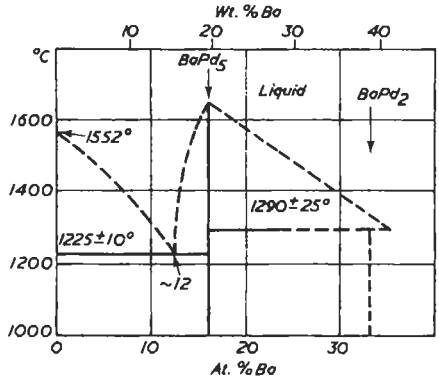
Ba–Na


°C
Wt. % Ba
At. % Ba
725°
BaNa
Liquid
BaNa4
197°
β
97·8°
82°
65°
5·5

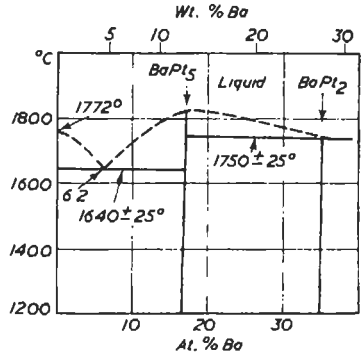
Ba–Pb


°C
Wt. % Pb
At % Pb
Ba2Pb
928°
BaPb
850°
36
Liquid
BaPb (H)
BaPb3
(676°)
595°
18
30
583°
69·5
617°
546°
~375°
375° Transf.
BaPb (L)
327°
293°
93
99·2
Pb

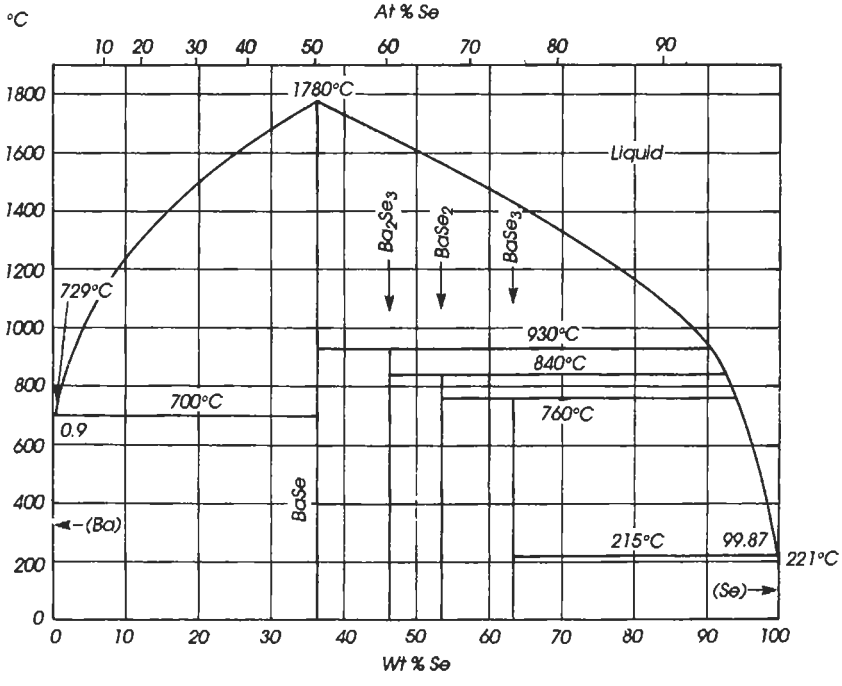
Ba–Pd



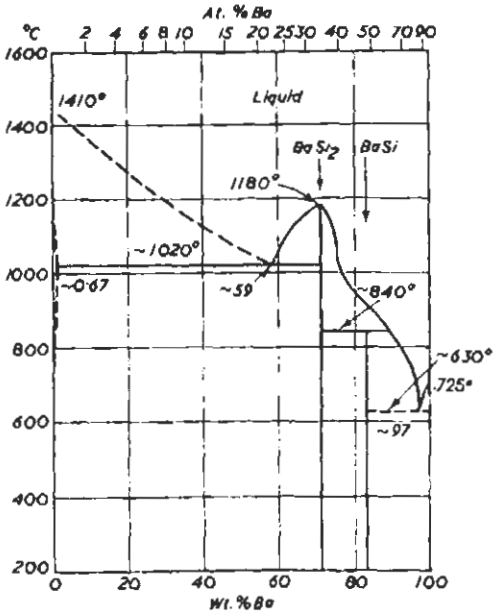
Ba–Pt



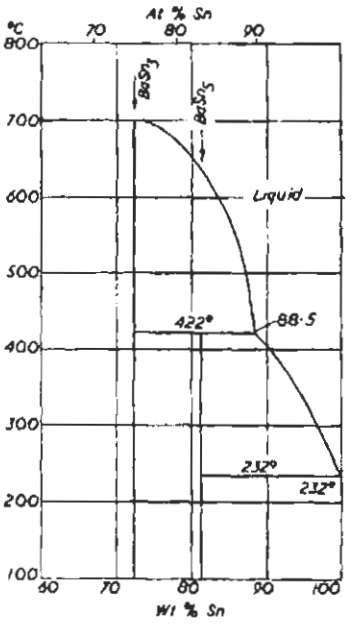
Ba–Se



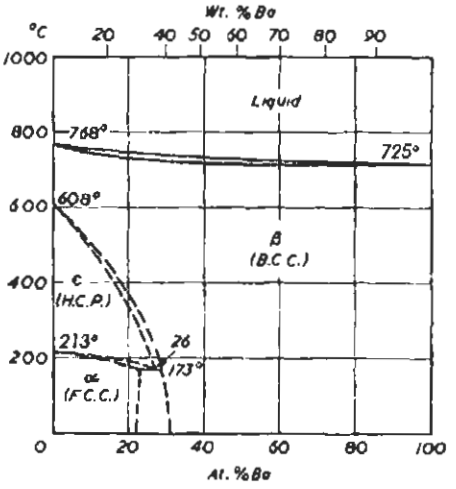
Ba–Si



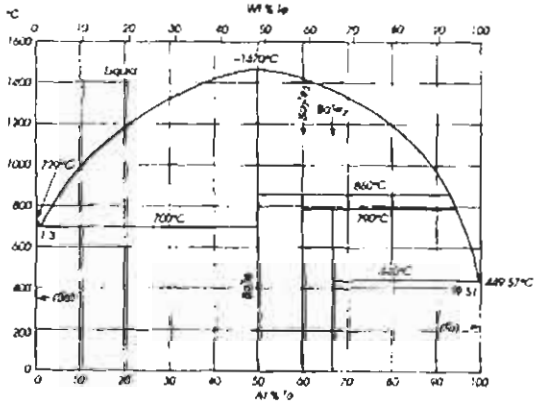
Ba–Sn



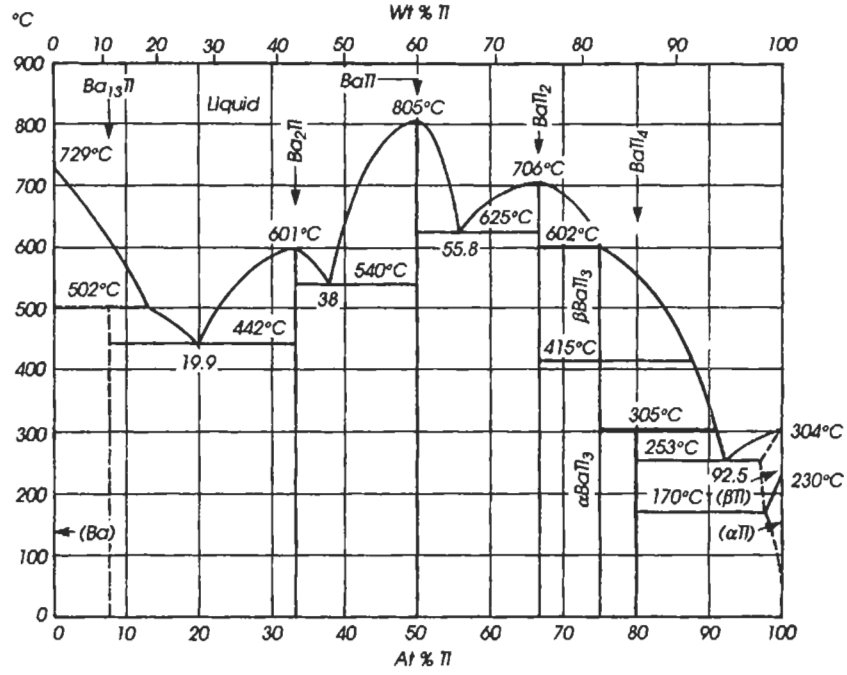
Ba–Sr



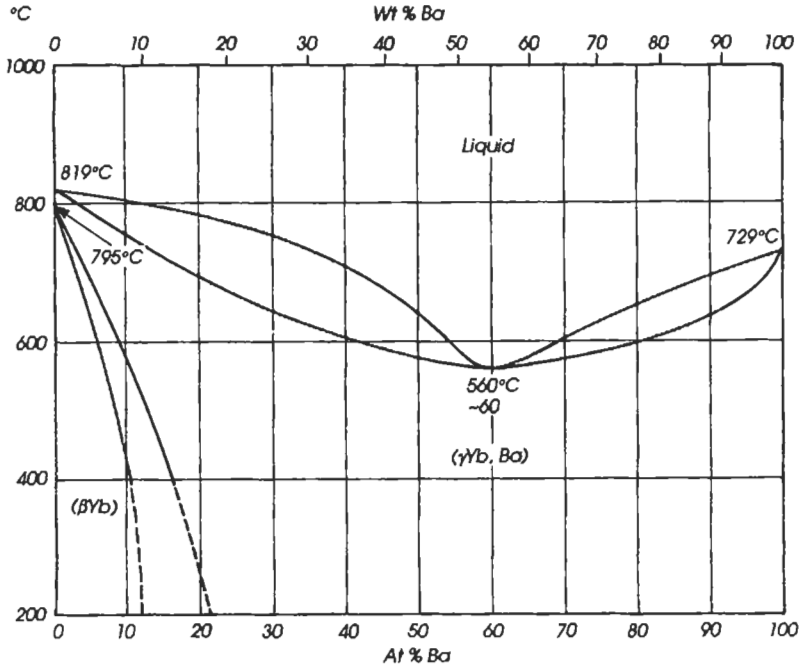
Ba–Te



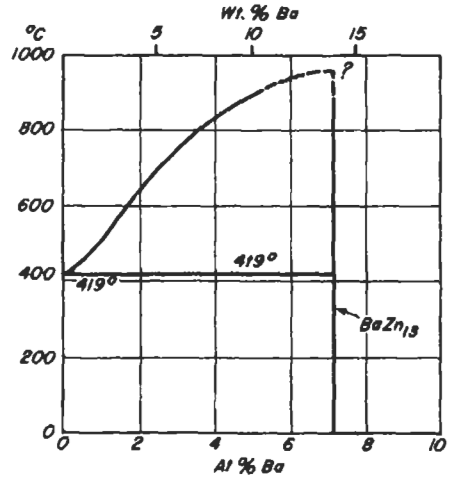
Ba–Tl


°C
Wt % Tl
0 10 20 30 40 50 60 70 80 90 100
900 800 700 600 500 400 300 200 100 0
$Ba_{13}Tl$
Liquid
Ba_2Tl
BaTl
805°C
$BaTl_2$
706°C
$BaTl_4$
729°C
601°C
625°C
602°C
55.8
540°C
502°C
38
442°C
βBaTl3
415°C
19.9
305°C
304°C
253°C
92.5
230°C
αBaTl3
170°C
(βTl)
(αTl)
(Ba)
At % Tl

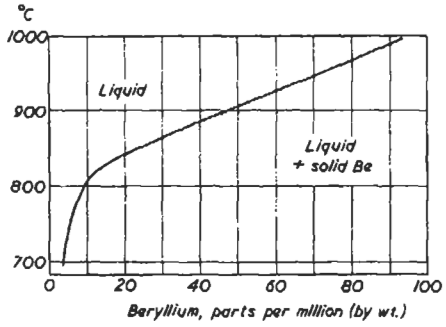
Ba–Yb


°C
Wt % Ba
0 10 20 30 40 50 60 70 80 90 100
1000 800 600 400 200
Liquid
819°C
795°C
729°C
560°C
~60
(γYb, Ba)
(βYb)
At % Ba

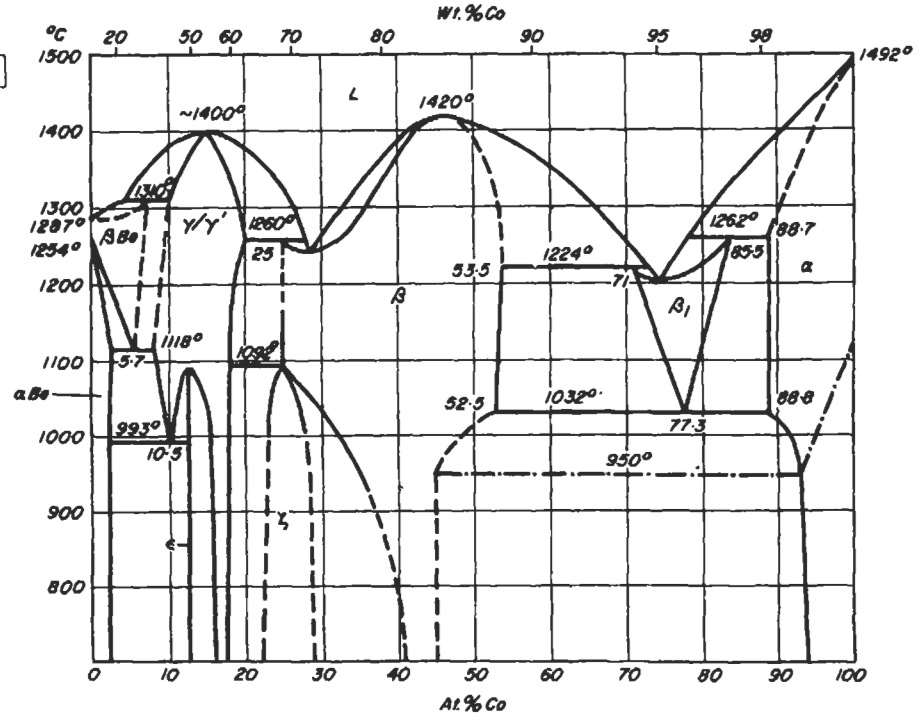
Ba–Zn



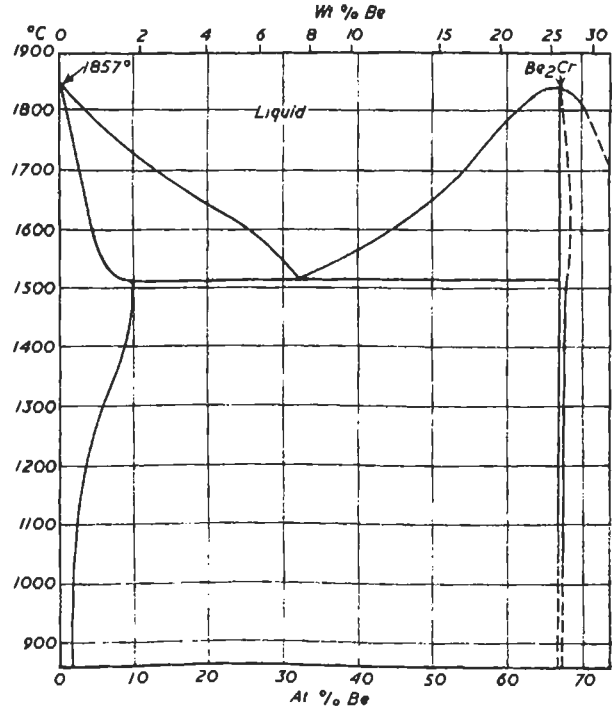
Be–Bi



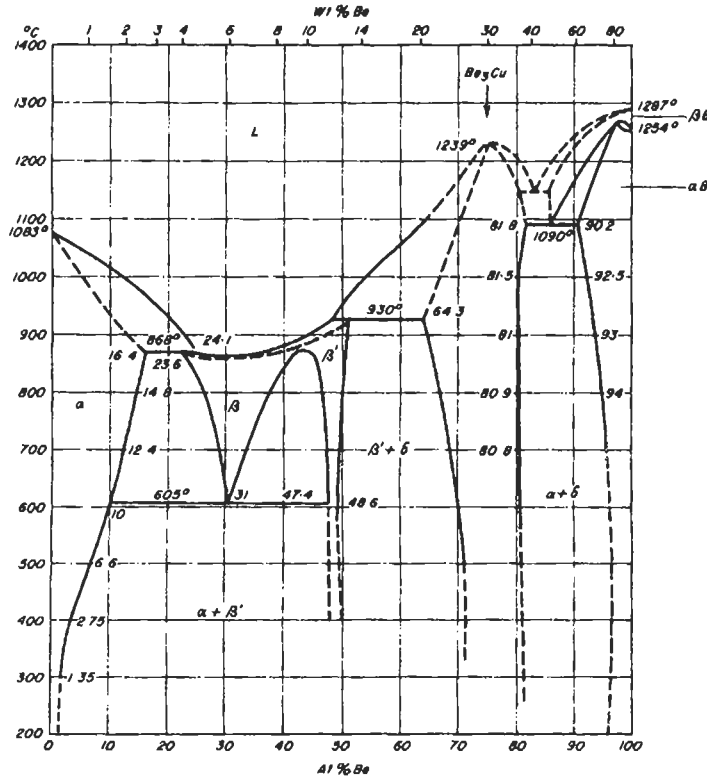
Be–Co



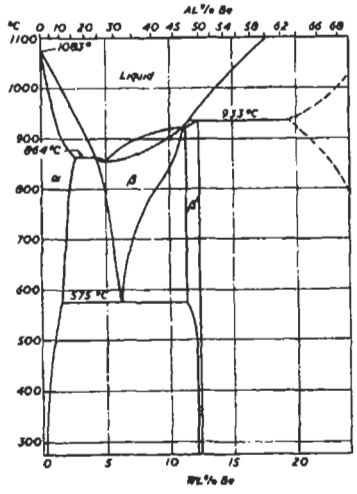
Be–Cr


Wt % Be
°C
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
0 2 4 6 8 10 15 20 25 30
1857°
Liquid
Be2Cr
0 10 20 30 40 50 60 70
At % Be

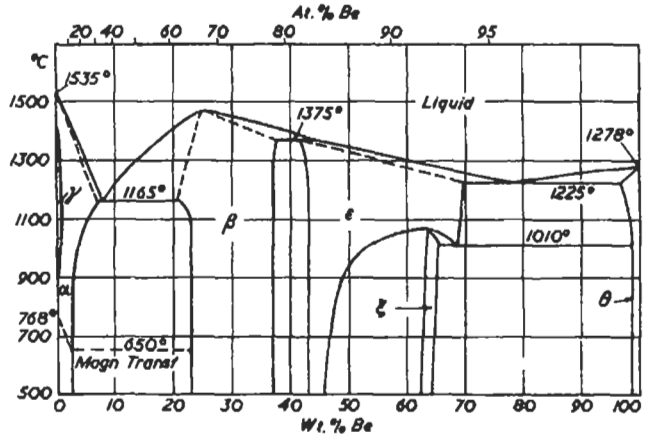
Be–Cu


Wt % Be
°C
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
1083°
L
Be2Cu
1287°
βBe
1254°
1239°
αBe
1090°
868°
930°
605°
α
β
β'
β'+δ
α+δ
α+β'
0 10 20 30 40 50 60 70 80 90 100
At % Be

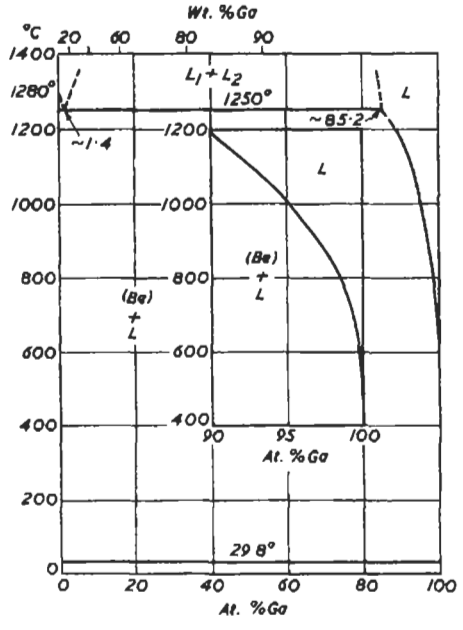
Be–Cu



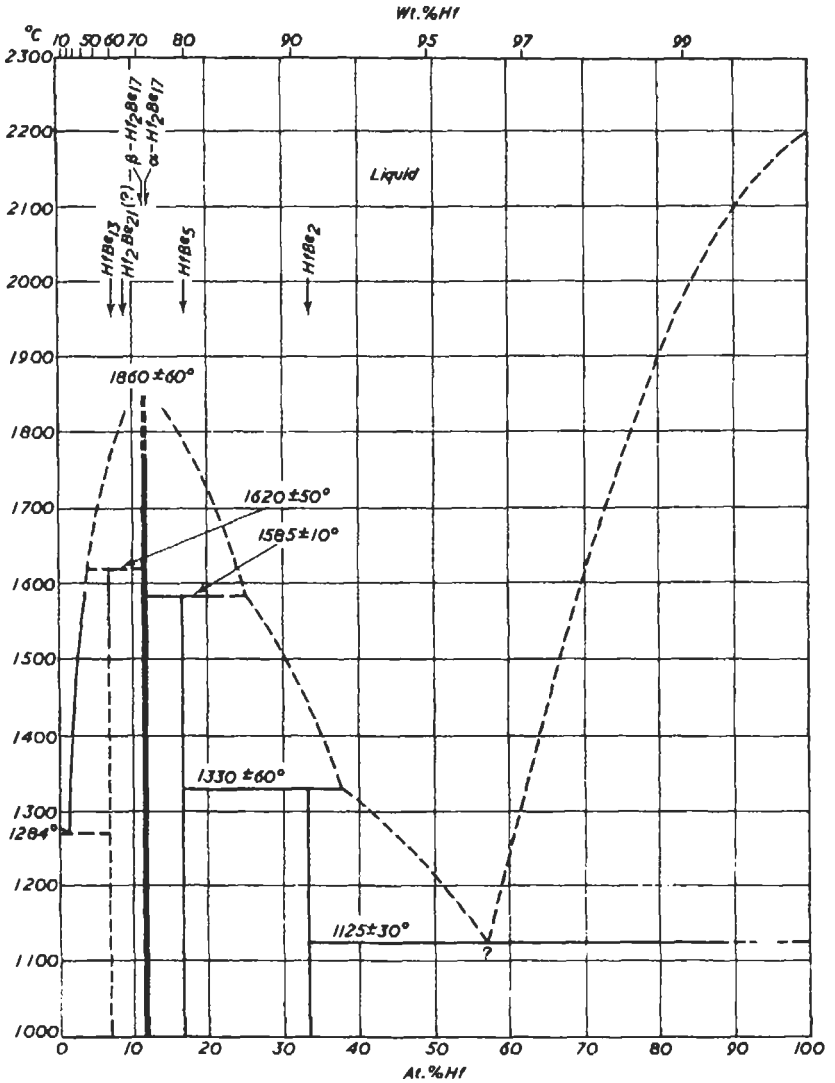
Be–Fe



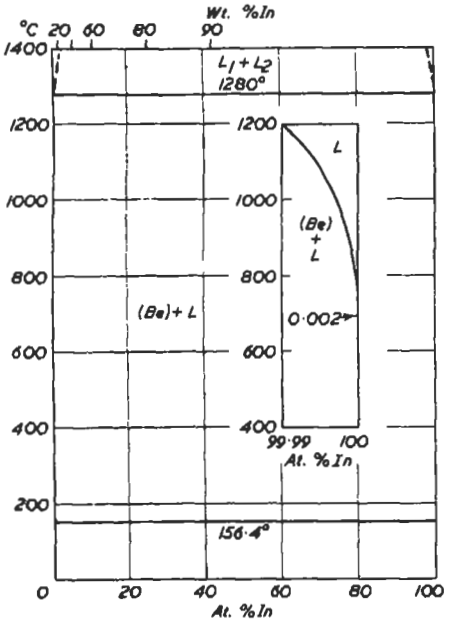
Be–Ga



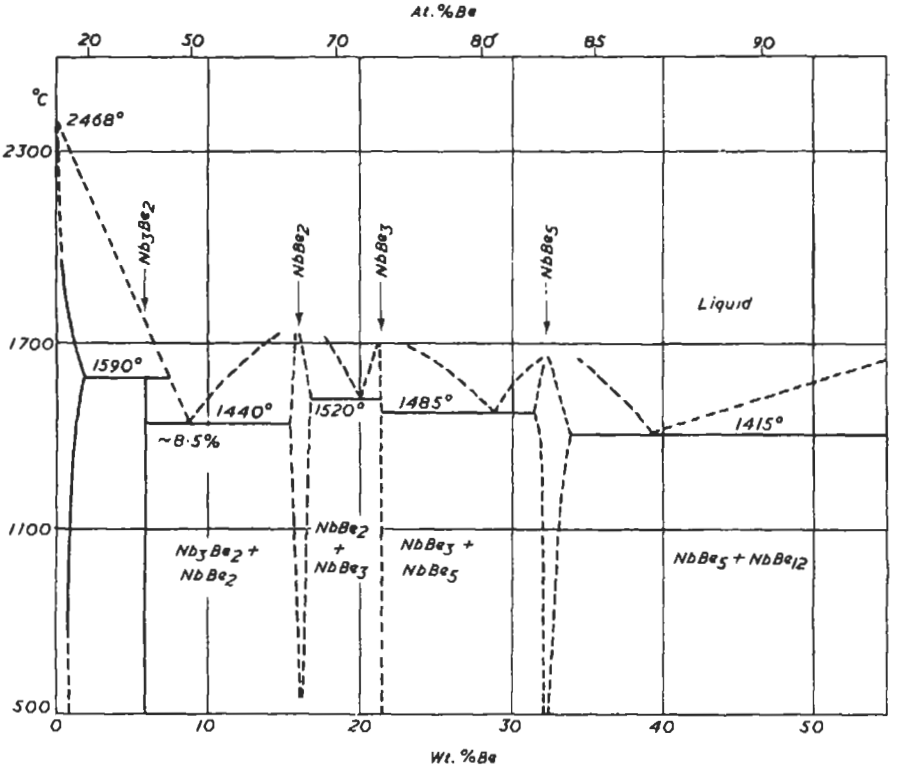
Be–Hf


Wt.%Hf
°C
10
50
60
70
80
90
95
97
99
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1284°
1200
1100
1000
Liquid
HfBe13
Hf2Be21 (?)
β-Hf2Be17
α-Hf2Be17
HfBe5
HfBe2
1860±60°
1620±50°
1585±10°
1330±60°
1125±30°
?
0
10
20
30
40
50
60
70
80
90
100
At.%Hf

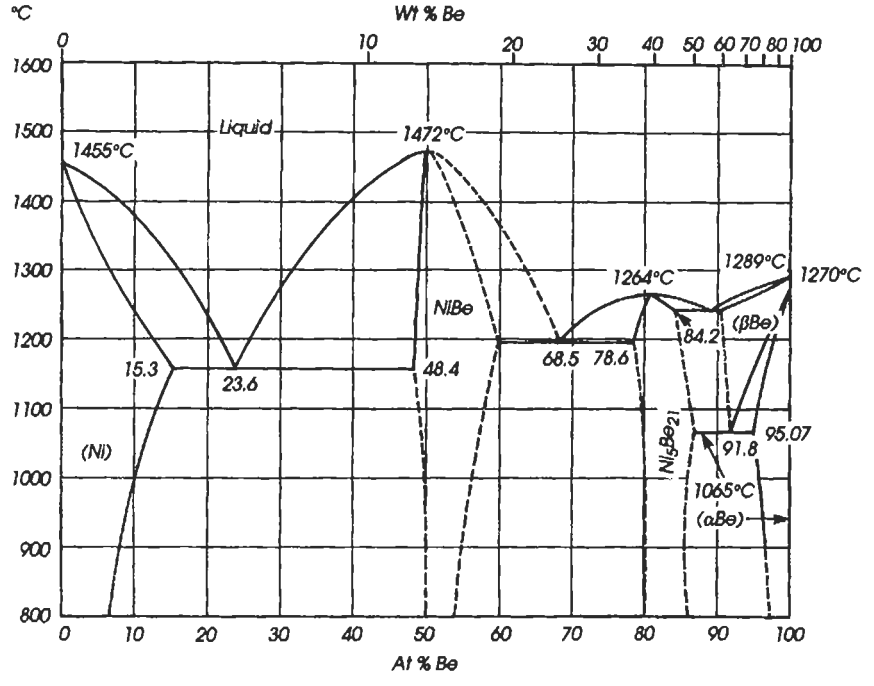
Be–In


°C 20 60 80 90
Wt. %In
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
At. %In
L1 + L2
1280°
L
(Be)
+
L
(Be)+ L
0·002
99·99
100
At. %In
156·4°

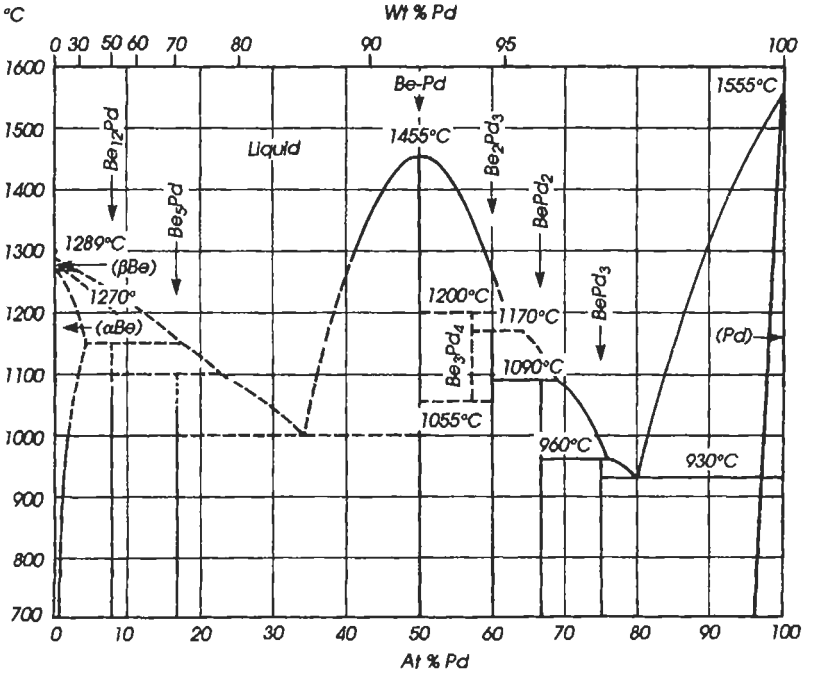
Be–Nb


At.%Be
20
50
70
80
85
90
°C
2468°
2300
Nb3Be2
NbBe2
NbBe3
NbBe5
Liquid
1700
1590°
1440°
~8·5%
1520°
1485°
1415°
1100
Nb3Be2 +
NbBe2
NbBe2
+
NbBe3
NbBe3 +
NbBe5
NbBe5 + NbBe12
500
0
10
20
30
40
50
Wt. %Be

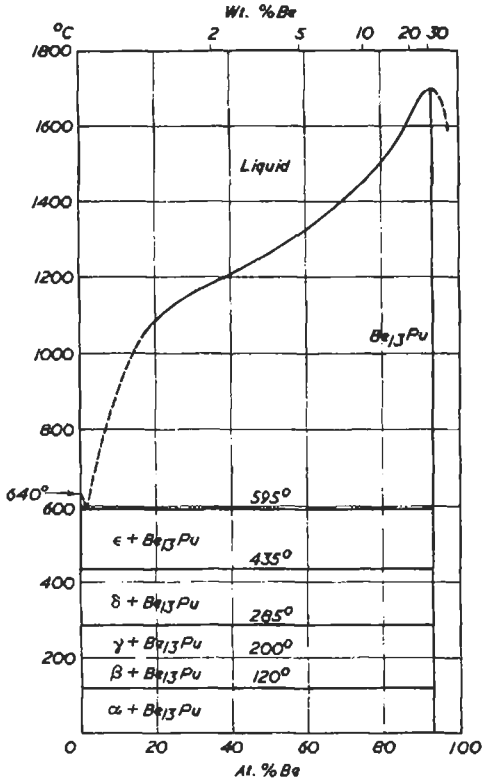
Be–Ni


°C
Wt % Be
0 10 20 30 40 50 60 70 80 100
1600
1500
1400
1300
1200
1100
1000
900
800
Liquid
1455°C
1472°C
1264°C
1289°C
1270°C
NiBe
(βBe)
84.2
15.3
23.6
48.4
68.5
78.6
(Ni)
Ni5Be21
95.07
91.8
1065°C
(αBe)
0 10 20 30 40 50 60 70 80 90 100
At % Be

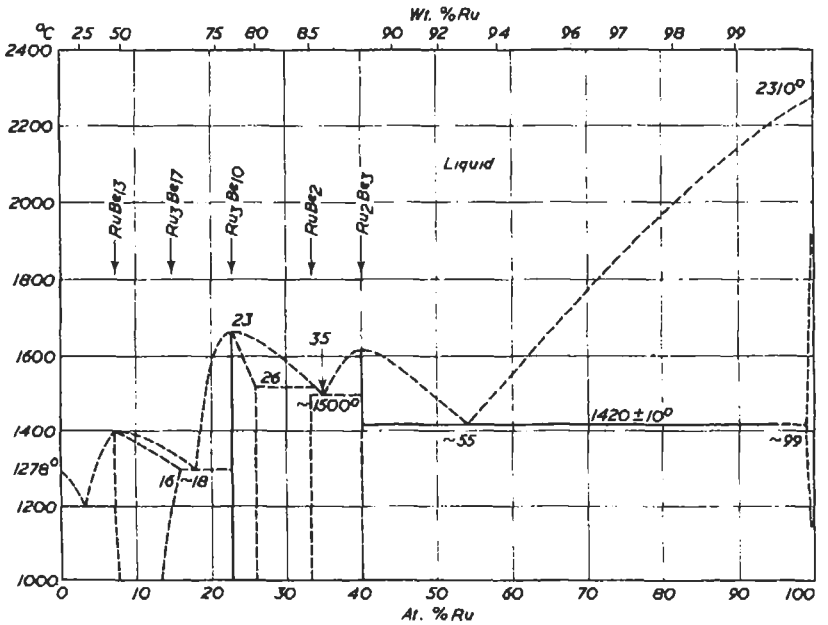
Be–Pd


°C
Wt % Pd
0 30 50 60 70 80 90 95 100
1600
1500
1400
1300
1200
1100
1000
900
800
700
Be-Pd
1555°C
1455°C
Liquid
Be12Pd
Be5Pd
Be2Pd3
BePd2
BePd3
1289°C
(βBe)
1270°
(αBe)
1200°C
1170°C
Be3Pd4
1090°C
(Pd)
1055°C
960°C
930°C
0 10 20 30 40 50 60 70 80 90 100
At % Pd

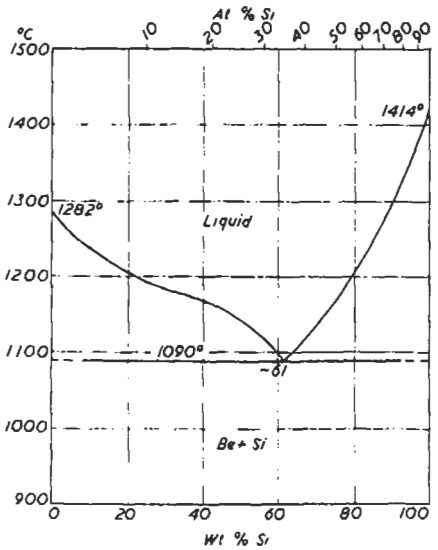
Be–Pu


Wt. % Be
°C
2
5
10
20
30
1800
1600
1400
1200
1000
800
640°
600
400
200
0
Liquid
Be13Pu
595°
ε + Be13Pu
435°
δ + Be13Pu
285°
γ + Be13Pu
200°
β + Be13Pu
120°
α + Be13Pu
20
40
60
80
100
At. % Be

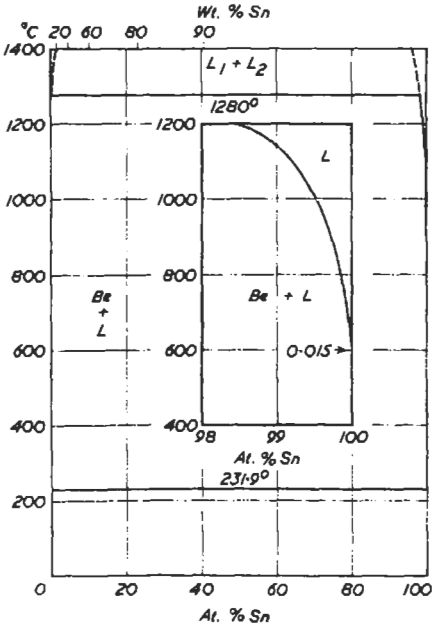
Be–Ru


Wt. % Ru
°C
25
50
75
80
85
90
92
94
96
97
98
99
2400
2200
2000
1800
1600
1400
1278°
1200
1000
RuBe13
Ru3Be17
Ru3Be10
RuBe2
Ru2Be3
Liquid
2310°
23
35
26
~1500°
16
~18
~55
1420 ± 10°
~99
0
10
20
30
40
50
60
70
80
90
100
At. % Ru

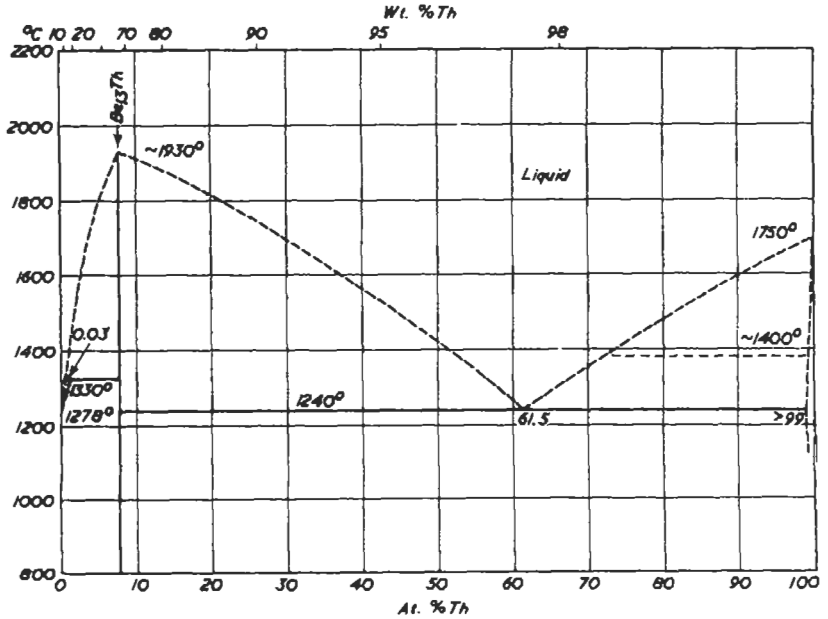
Be–Si



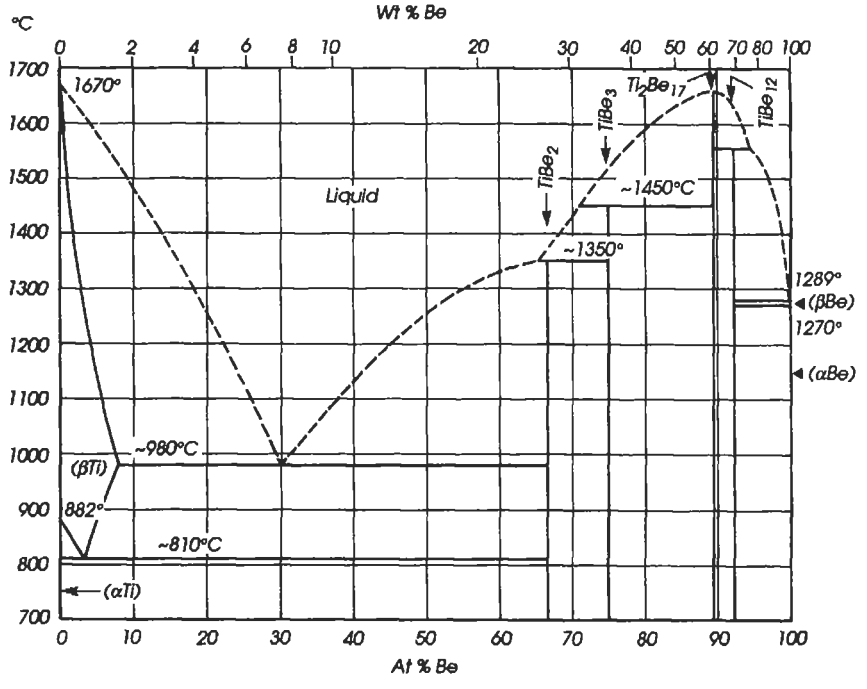
Be–Sn



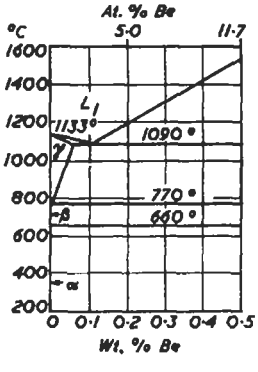
Be–Th



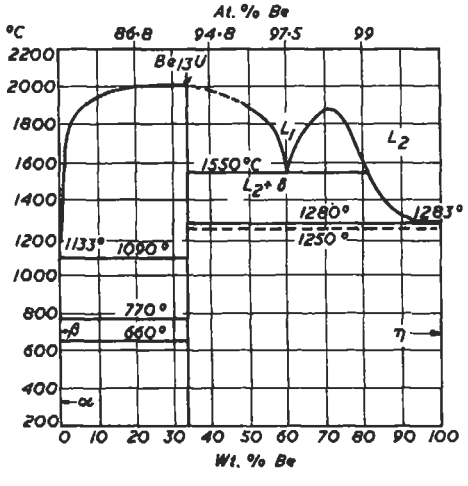
Be–Ti


°C
Wt % Be
0 2 4 6 8 10 20 30 40 50 60 70 80 100
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
1670°
Liquid
TiBe2
TiBe3
Ti2Be17
TiBe12
~1450°C
~1350°
1289°
(βBe)
1270°
(αBe)
~980°C
(βTi)
882°
~810°C
(αTi)
0 10 20 30 40 50 60 70 80 90 100
At % Be

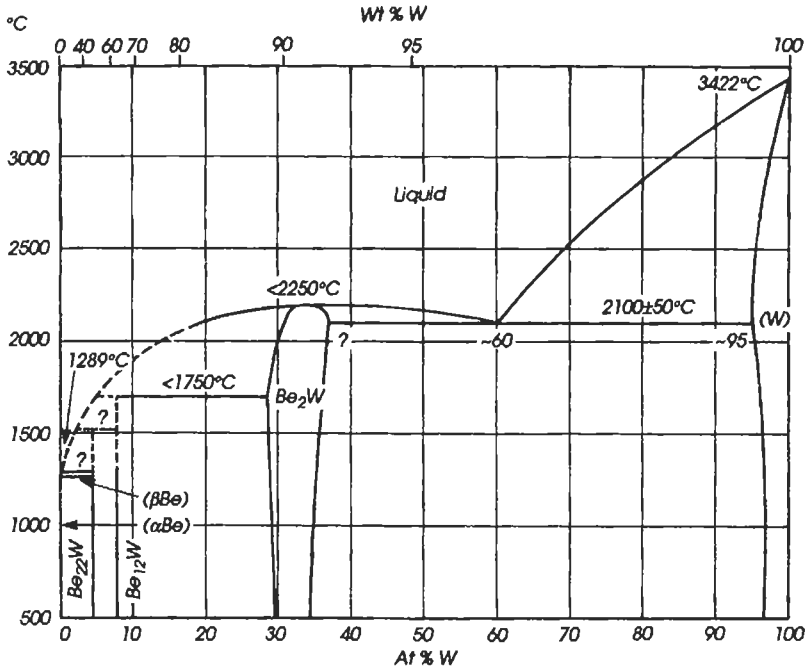
Be–U


At. % Be
°C
5·0
11·7
1600
1400
1200
1000
800
600
400
200
L1
1133°
1090°
γ
770°
β
660°
α
0 0·1 0·2 0·3 0·4 0·5
Wt. % Be

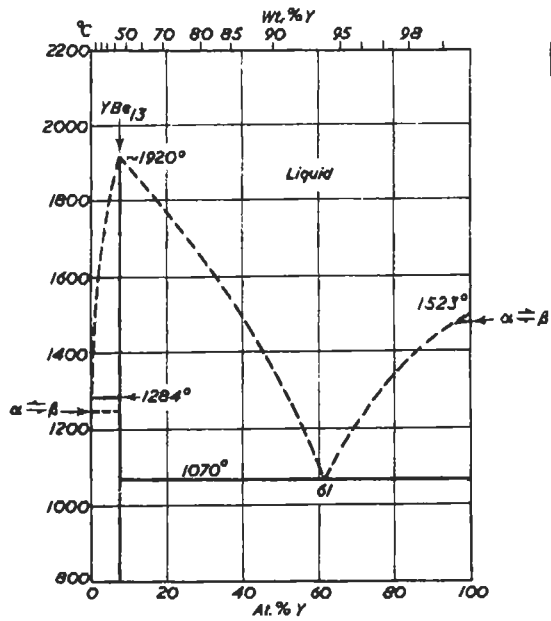
Be–U


At. % Be
°C
86·8
94·8
97·5
99
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
Be13U
L1
L2
1550°C
L2+δ
1280°
1283°
1250°
1133°
1090°
770°
β
660°
α
η
0 10 20 30 40 50 60 70 80 90 100
Wt. % Be

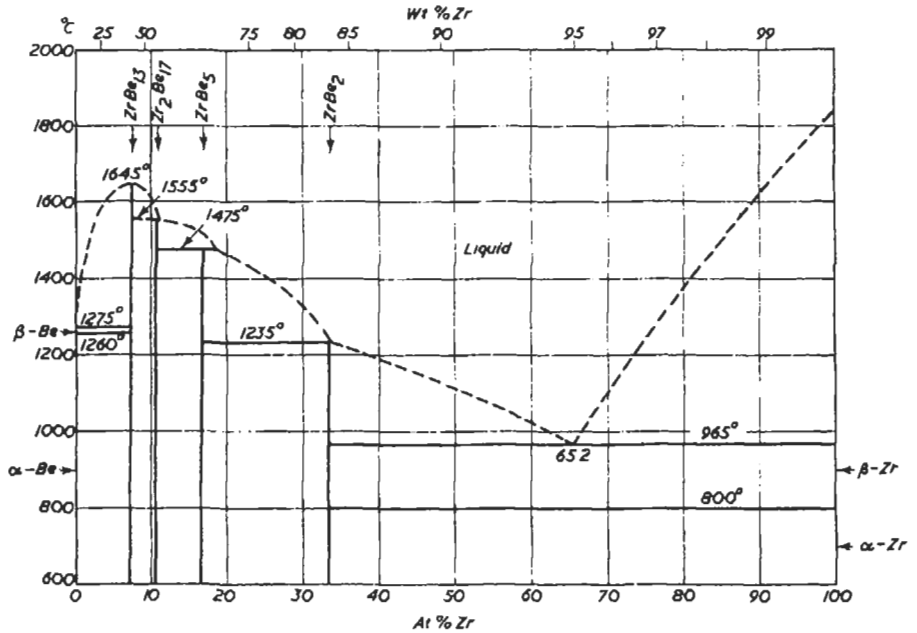
Be–W


°C
Wt % W
0 40 60 70 80 90 95 100
3500
3000
2500
2000
1500
1000
500
3422°C
Liquid
<2250°C
2100±50°C
(W)
?
~60
~95
1289°C
<1750°C
Be2W
?
?
(βBe)
(αBe)
Be22W
Be12W
0 10 20 30 40 50 60 70 80 90 100
At % W

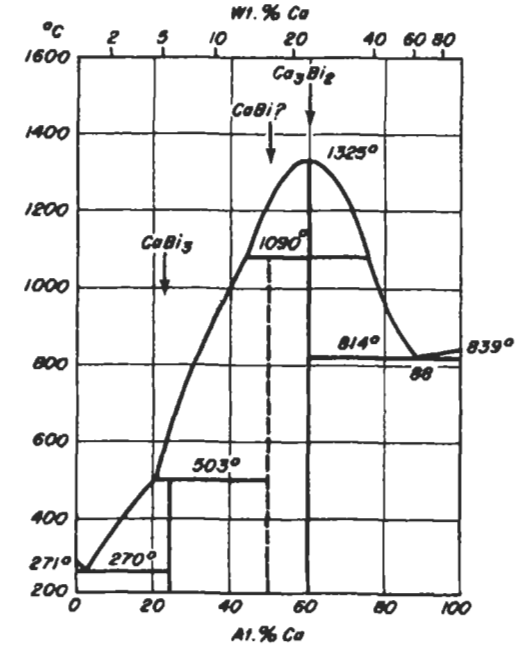
Be–Y


°C
Wt. % Y
50 70 80 85 90 95 98
2200
2000
1800
1600
1400
1200
1000
800
YBe13
~1920°
Liquid
1523°
α ⇌ β
α ⇌ β
1284°
1070°
61
0 20 40 60 80 100
At. % Y

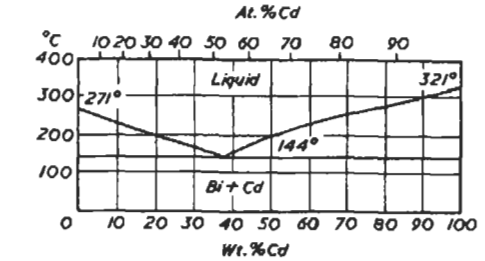
Be–Zr



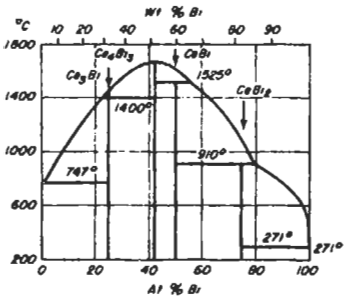
Bi–Ca



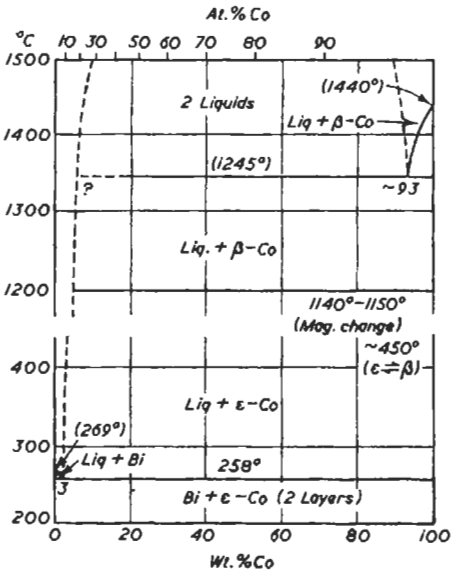
Bi–Cd



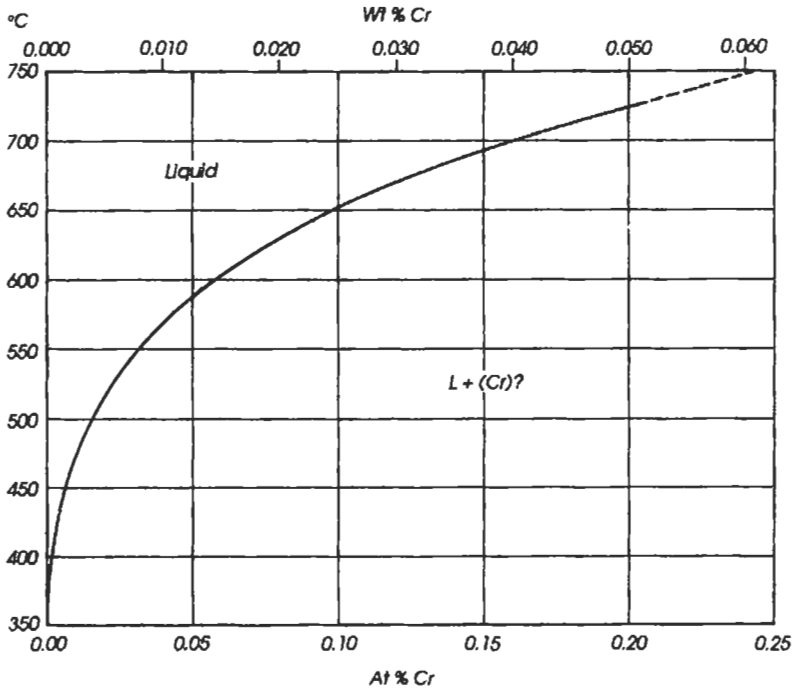
Bi–Ce



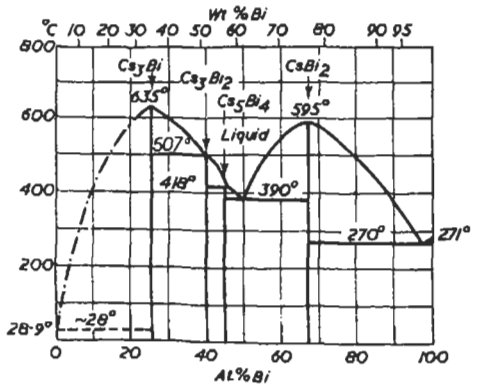
Bi–Co



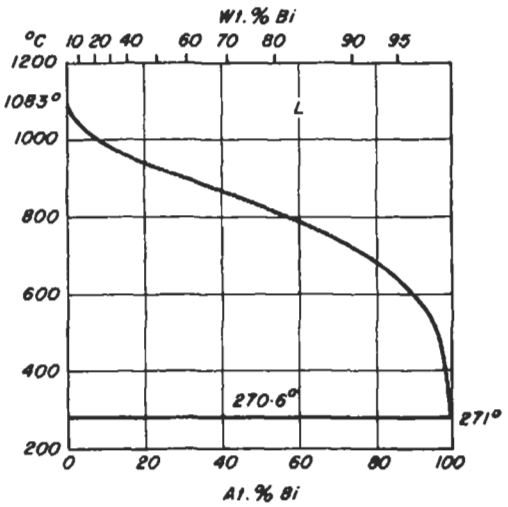
Bi–Cr



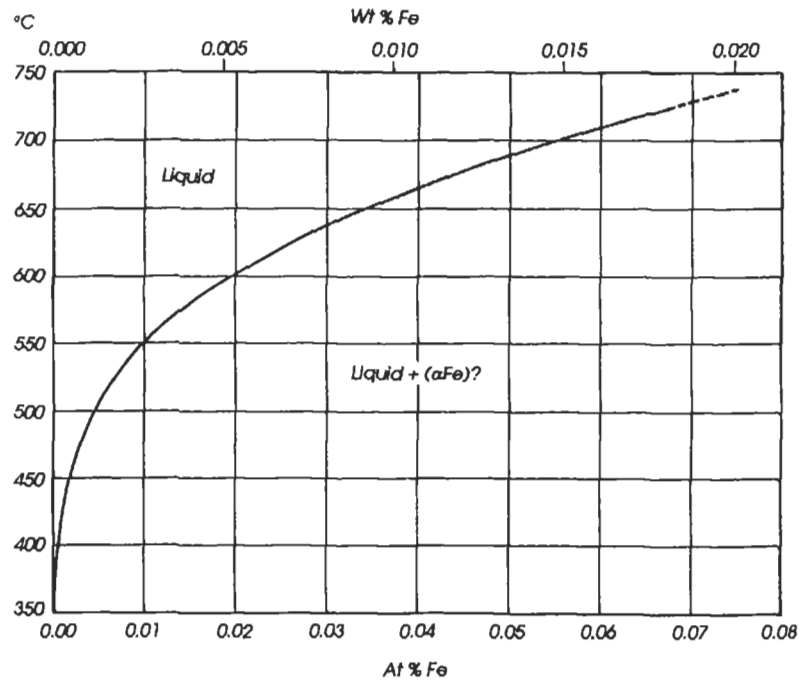
Bi–Cs



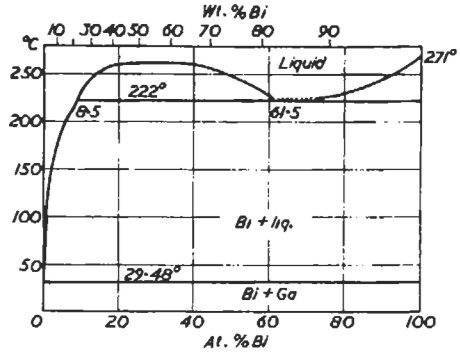
Bi–Cu



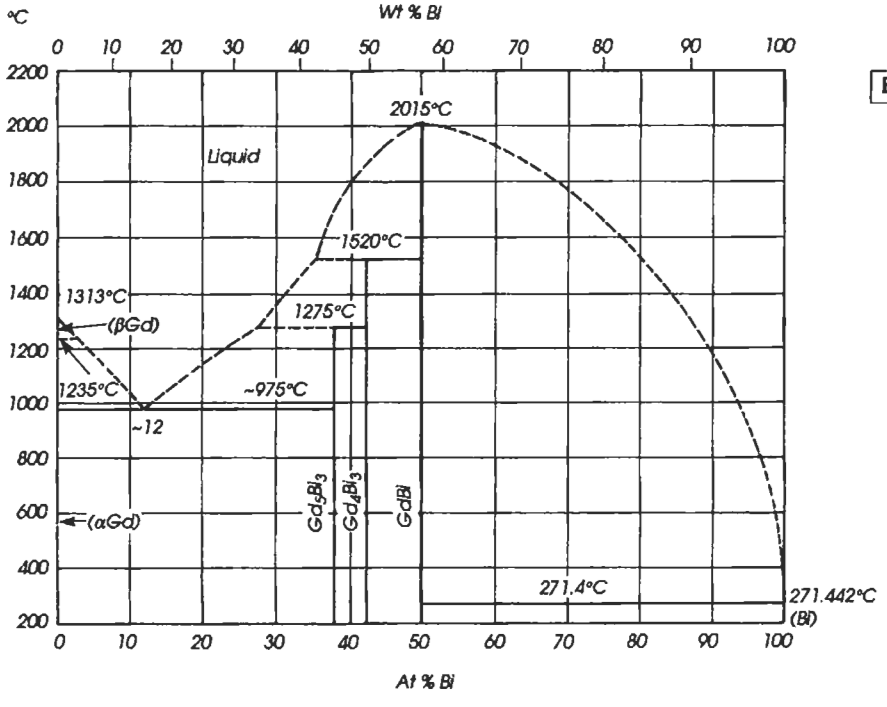
Bi–Fe



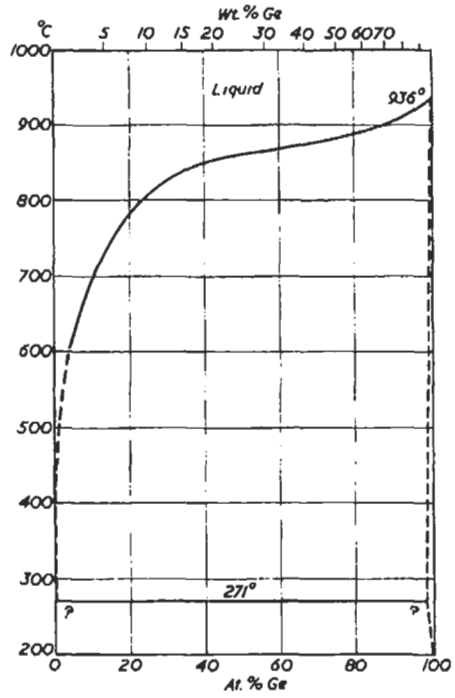
Bi–Ga


Wt. % Bi
°C
10 30 40 50 60 70 80 90
250
200
150
100
50
Liquid
271°
222°
8·5
61·5
Bi + liq.
29·48°
Bi + Ga
0 20 40 60 80 100
At. % Bi

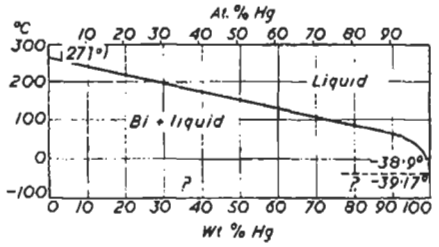
Bi–Gd


°C
Wt % Bi
0 10 20 30 40 50 60 70 80 90 100
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
2015°C
Liquid
1520°C
1313°C
(βGd)
1275°C
1235°C
~975°C
~12
(αGd)
Gd5Bi3
Gd4Bi3
GdBi
271.4°C
271.442°C
(Bi)
0 10 20 30 40 50 60 70 80 90 100
At % Bi

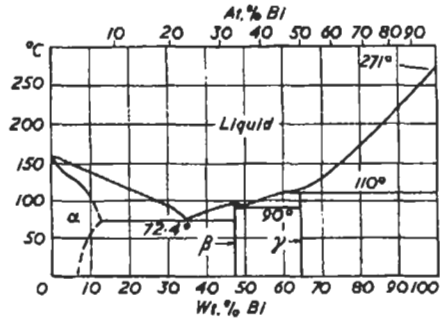
Bi–Ge



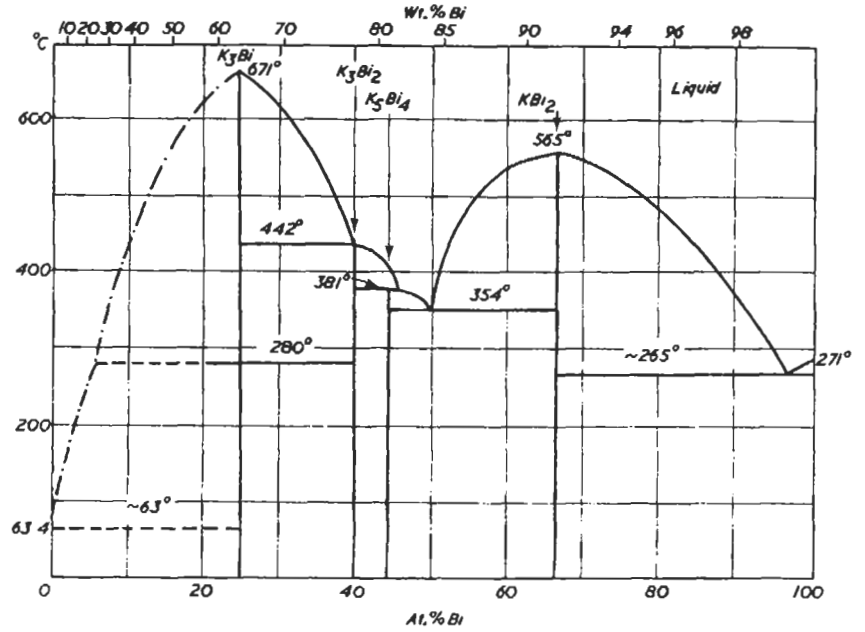
Bi–Hg



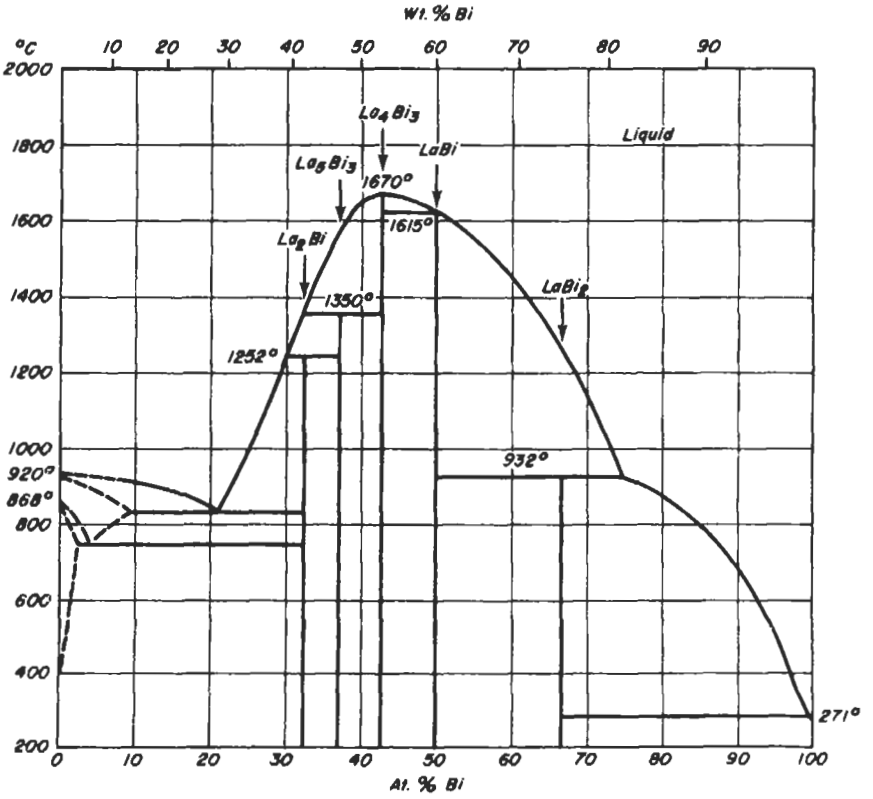
Bi–In



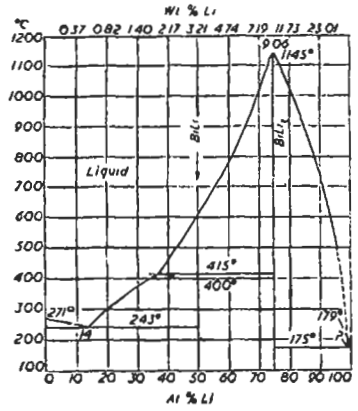
Bi–K


Wt. % Bi
°C
10 20 30 40 50 60 70 80 85 90 94 96 98
K_3Bi
671°
K_3Bi_2
K_5Bi_4
KBi_2
Liquid
565°
442°
381°
354°
280°
~265°
271°
~63°
63.4
600
400
200
0
20
40
60
80
100
At. % Bi

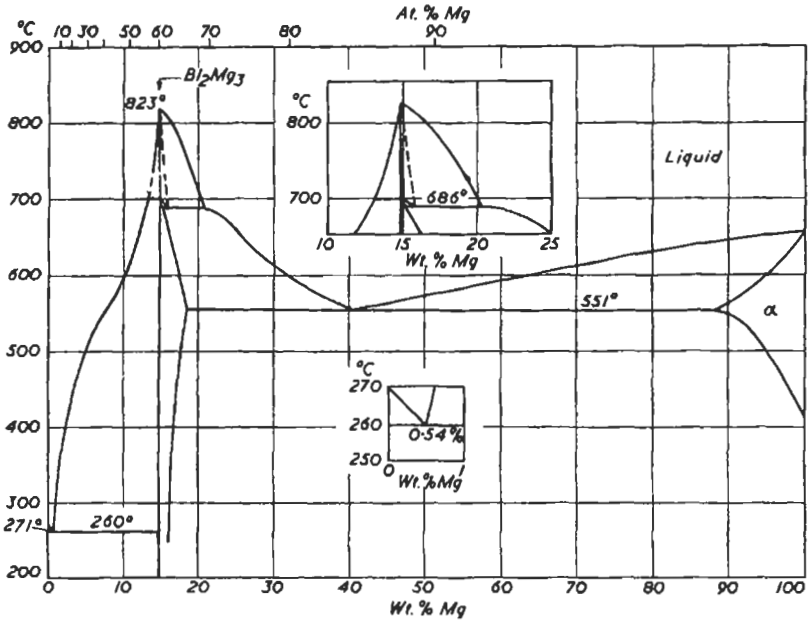
Bi–La


Wt. % Bi
°C
10 20 30 40 50 60 70 80 90
La_4Bi_3
LaBi
Liquid
La_5Bi_3
1670°
1615°
La_2Bi
1350°
$LaBi_2$
1252°
932°
920°
868°
271°
2000
1800
1600
1400
1200
1000
800
600
400
200
0 10 20 30 40 50 60 70 80 90 100
At. % Bi

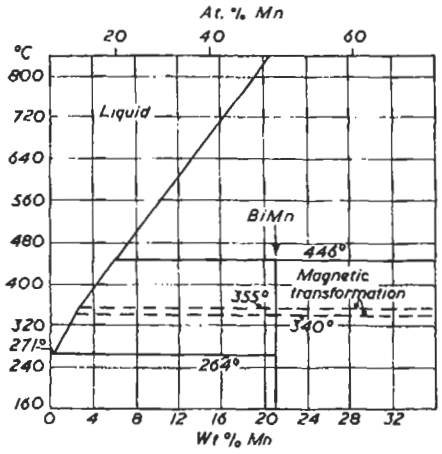
Bi–Li



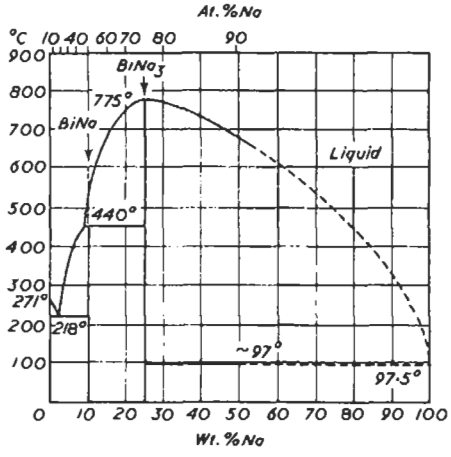
Bi–Mg



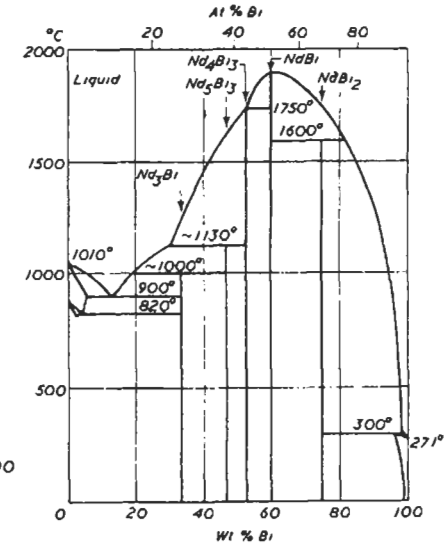
Bi–Mn



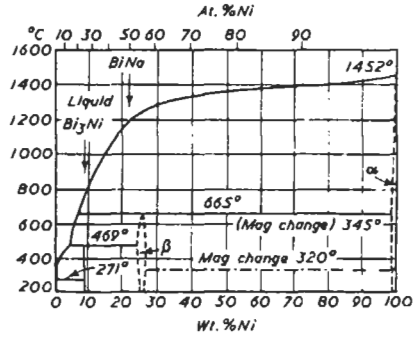
Bi–Na



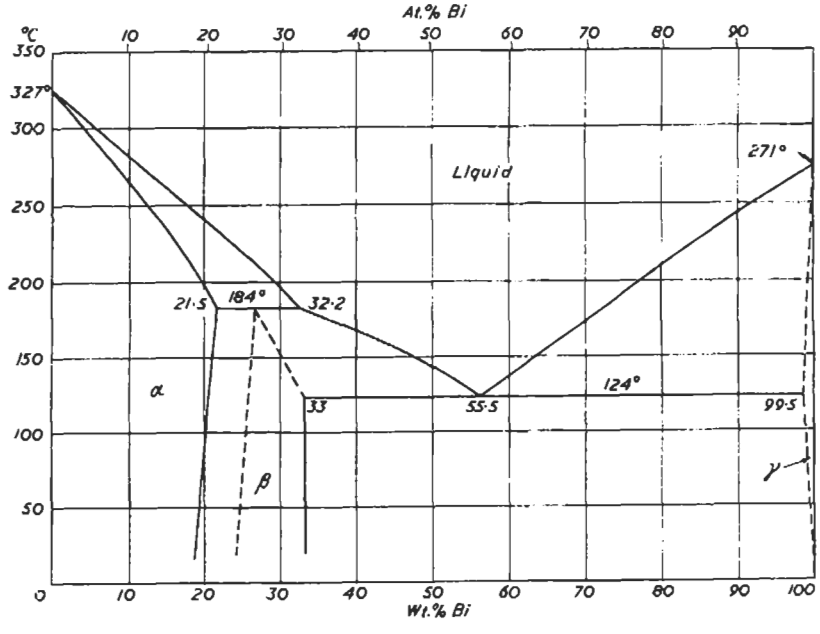
Bi–Nd



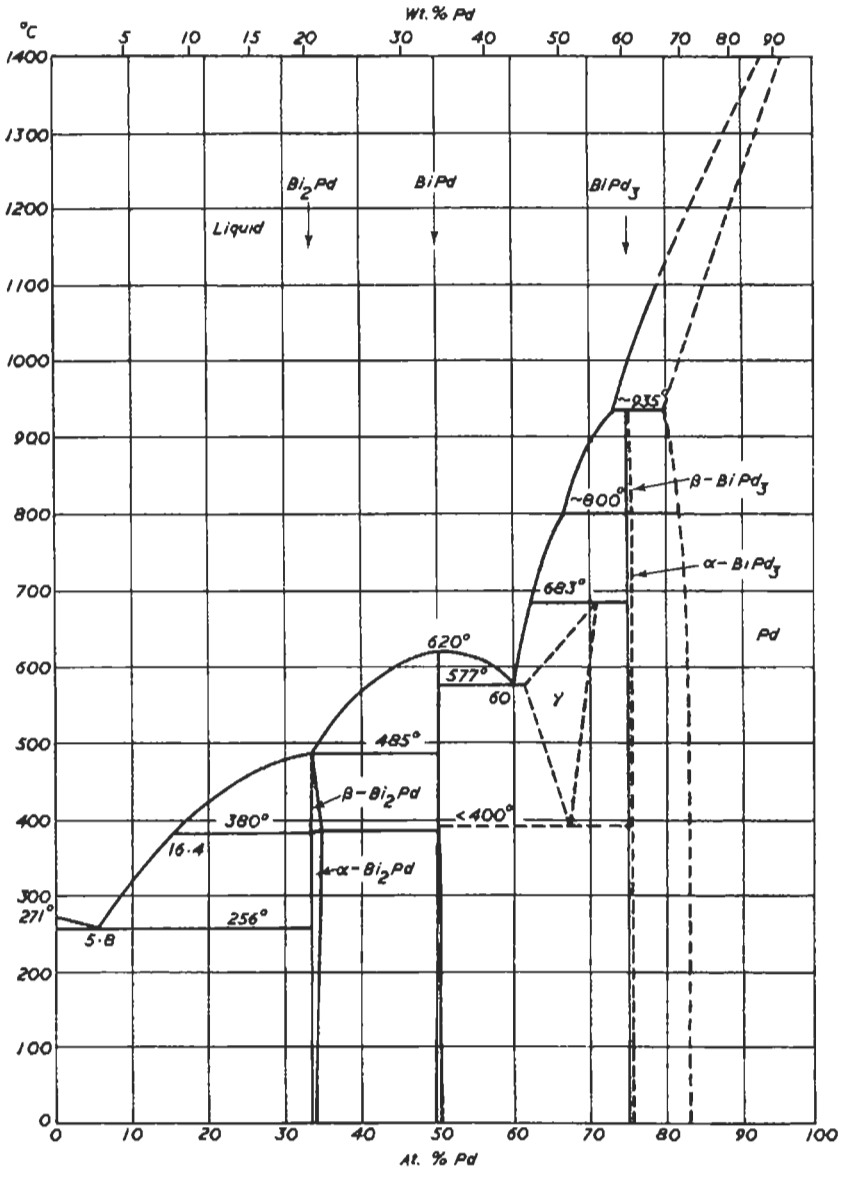
Bi–Ni



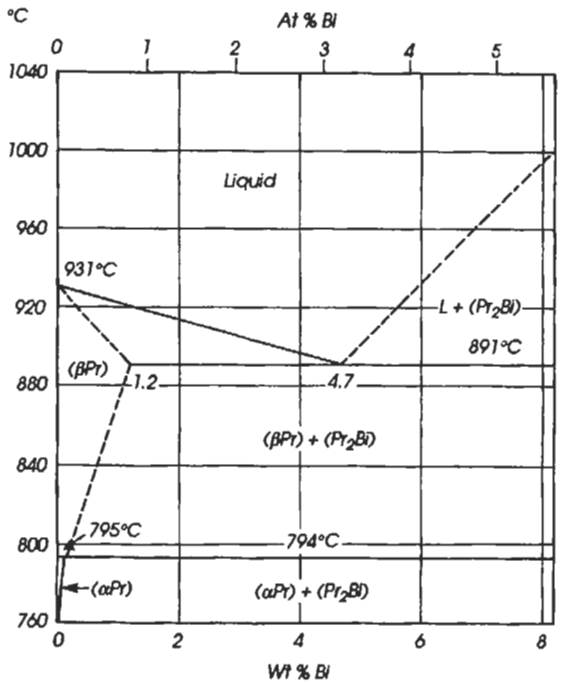
Bi–Pb



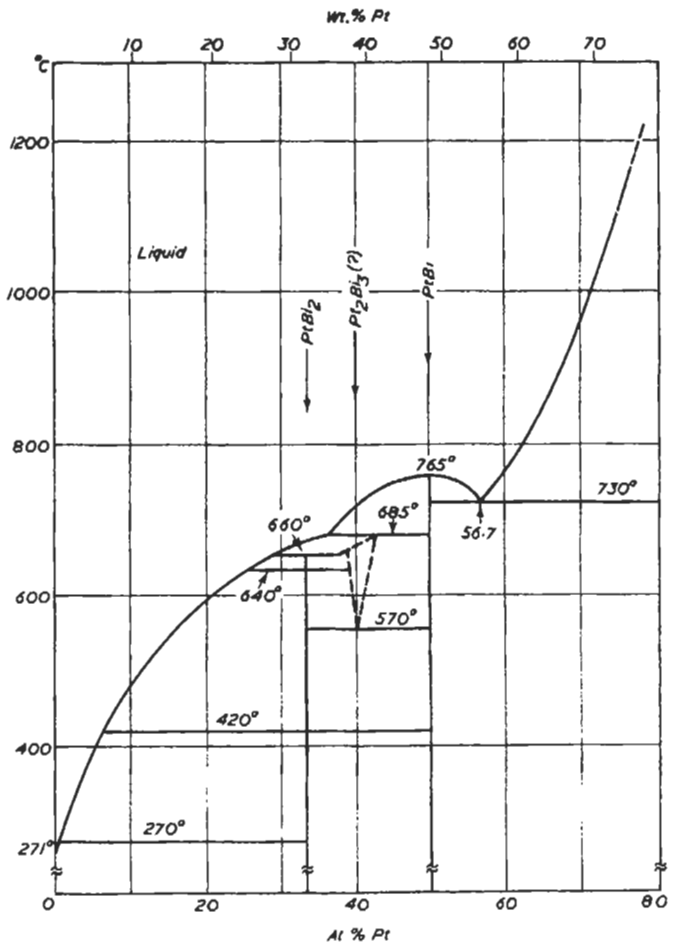
Bi–Pd


°C
Wt. % Pd
At. % Pd
Liquid
Bi_2Pd
BiPd
$BiPd_3$
~935°
~800°
β – $BiPd_3$
α – $BiPd_3$
683°
Pd
620°
577°
60
γ
485°
β – Bi_2Pd
380°
< 400°
16·4
α – Bi_2Pd
271°
256°
5·8

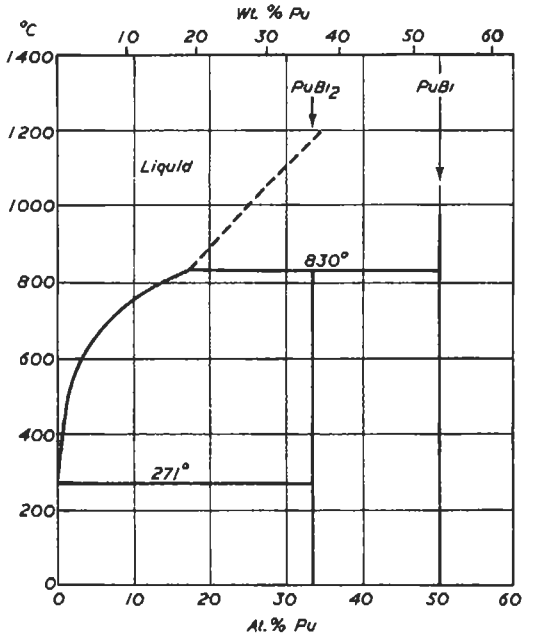
Bi–Pr


°C
At % Bi
0
1
2
3
4
5
1040
1000
960
920
880
840
800
760
Liquid
931°C
L + (Pr2Bi)
891°C
(βPr)
1.2
4.7
(βPr) + (Pr2Bi)
795°C
794°C
(αPr)
(αPr) + (Pr2Bi)
0
2
4
6
8
Wt % Bi

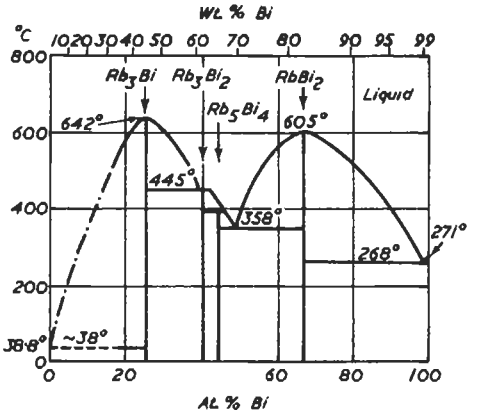
Bi–Pt


Wt.% Pt
10
20
30
40
50
60
70
°C
1200
1000
800
600
400
271°
Liquid
PtBi2
Pt2Bi3 (?)
PtBi
765°
730°
660°
685°
56·7
640°
570°
420°
270°
0
20
40
60
80
At % Pt

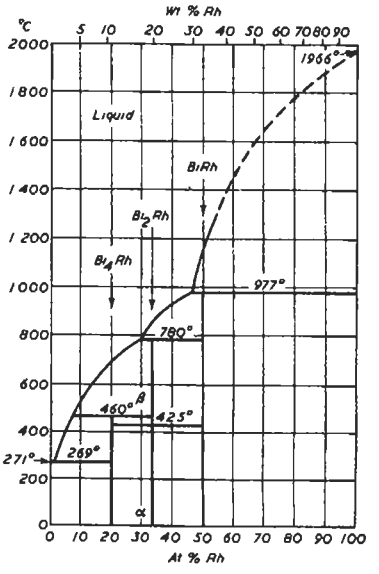
Bi–Pu

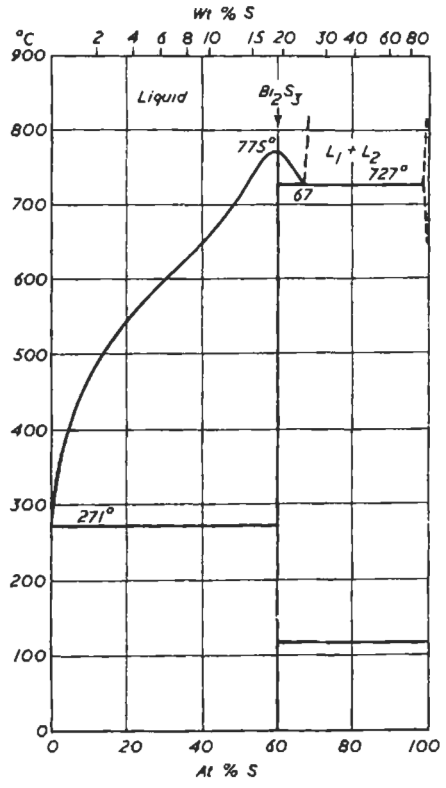


Bi–Rb

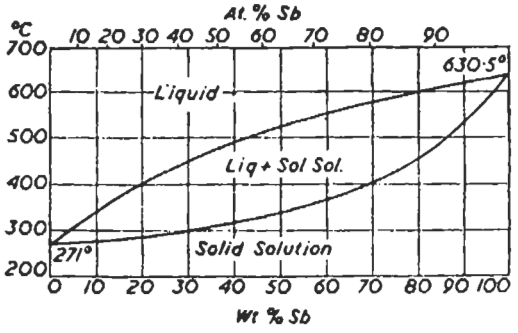


Bi–Rh



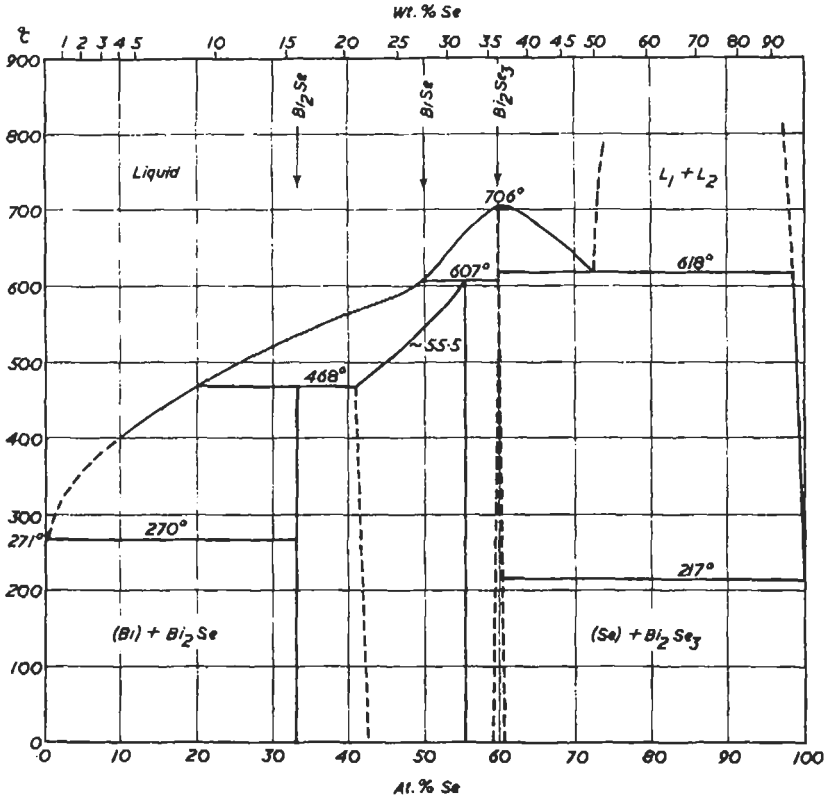

Wt % S
°C
2 4 6 8 10 15 20 30 40 60 80
900
800
700
600
500
400
300
200
100
0
Liquid
Bi_2S_3
775°
$L_1 + L_2$
727°
67
271°
0 20 40 60 80 100
At % S

Bi–S

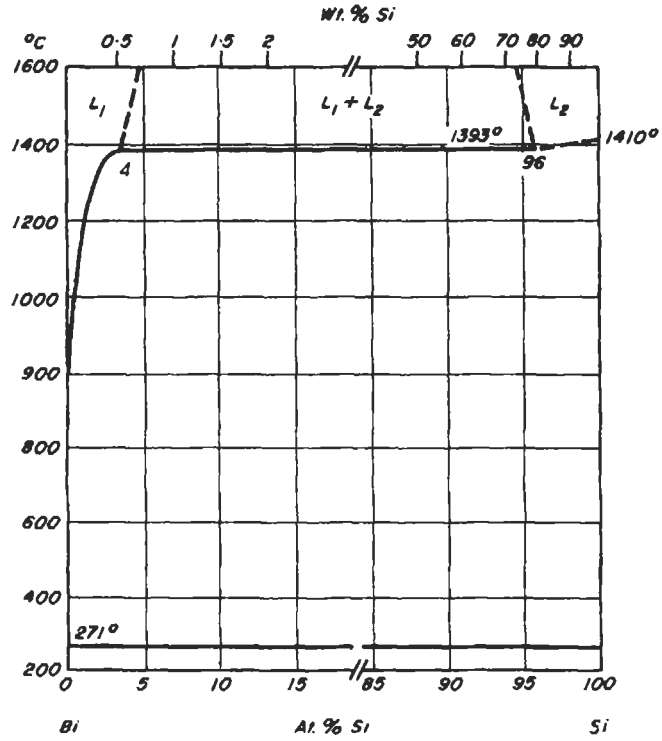

At. % Sb
°C
10 20 30 40 50 60 70 80 90
700
600
500
400
300
200
630·5°
Liquid
Liq + Sol Sol.
271°
Solid Solution
0 10 20 30 40 50 60 70 80 90 100
Wt % Sb

Bi–Sb

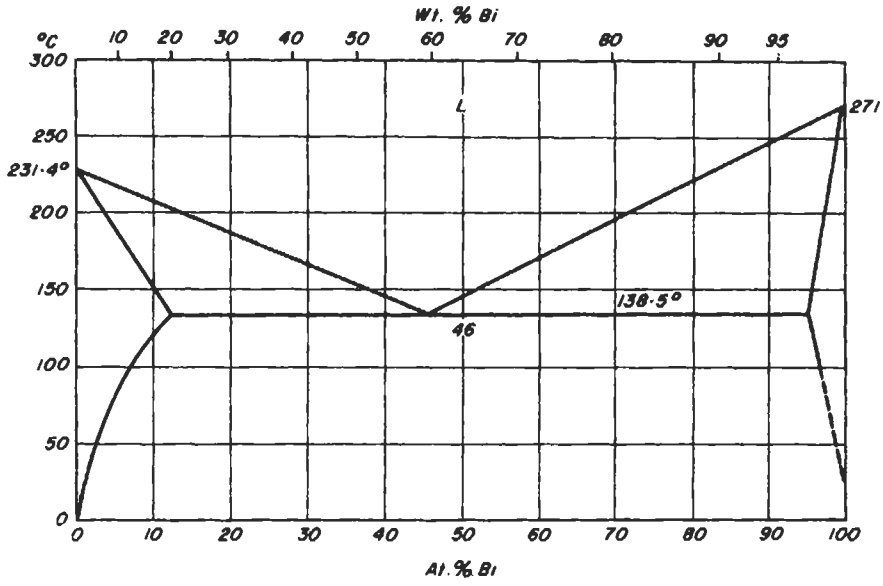
Bi–Se


Wt. % Se
°C
1 2 3 4 5 10 15 20 25 30 35 40 45 50 60 70 80 90
900
800
700
600
500
400
300
271°
200
100
0
Bi2Se
BiSe
Bi2Se3
Liquid
L1 + L2
706°
607°
618°
~55·5
468°
270°
217°
(Bi) + Bi2Se
(Se) + Bi2Se3
0 10 20 30 40 50 60 70 80 90 100
At. % Se

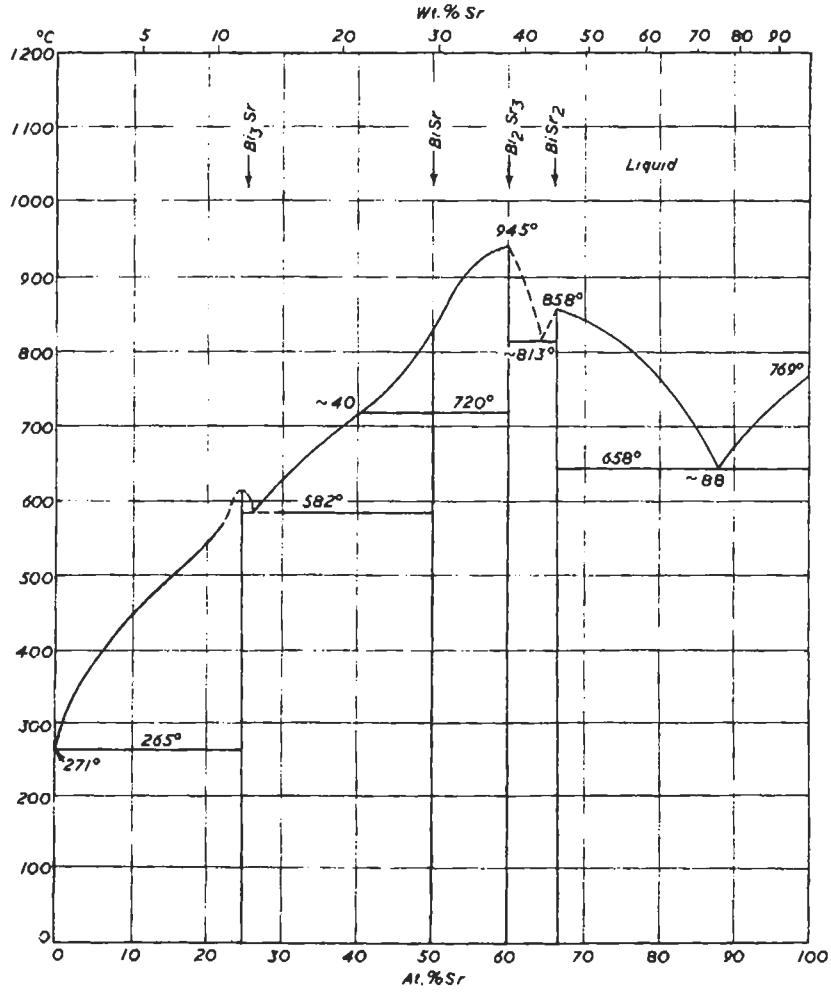
Bi–Si


Wt. % Si
°C
0·5 1 1·5 2 50 60 70 80 90
1600
1400
1200
1000
900
800
600
400
271°
200
L1
L1 + L2
L2
1393°
1410°
4
96
0 5 10 15 85 90 95 100
Bi
At. % Si
Si

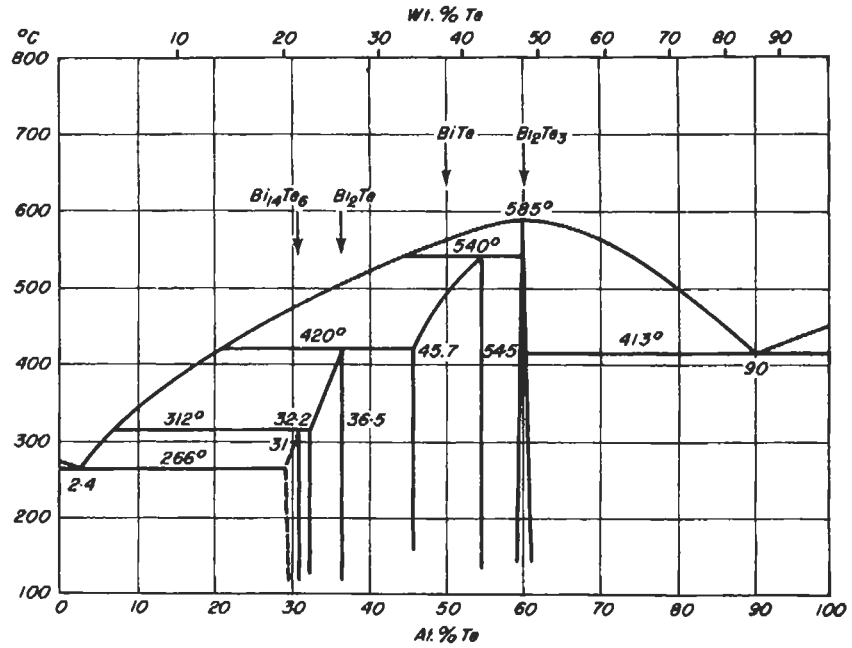
Bi–Sn


Wt. % Bi
°C
L
271°
231·4°
138·5°
46
At. % Bi

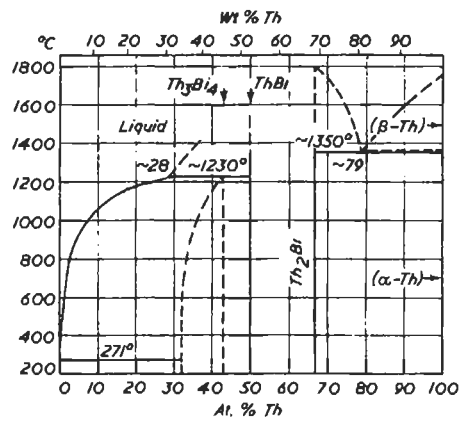
Bi–Sr


Wt. % Sr
°C
Bi3Sr
BiSr
Bi2Sr3
BiSr2
Liquid
945°
858°
~813°
769°
~40
720°
658°
~88
582°
265°
271°
At. % Sr

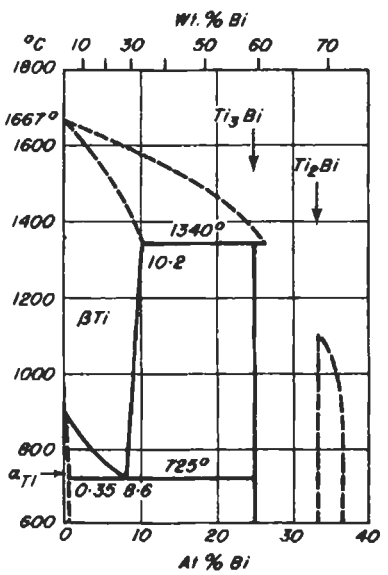
Bi–Te



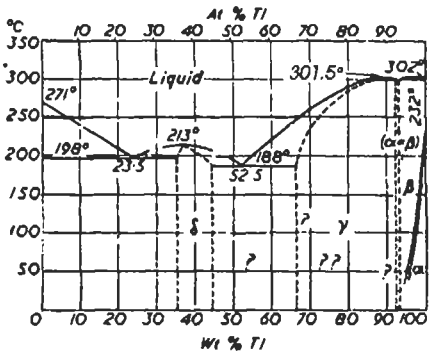
Bi–Th



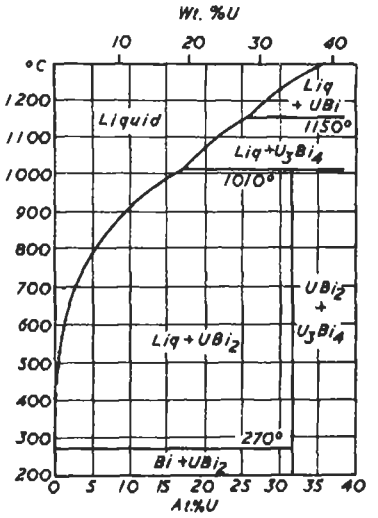
Bi–Ti



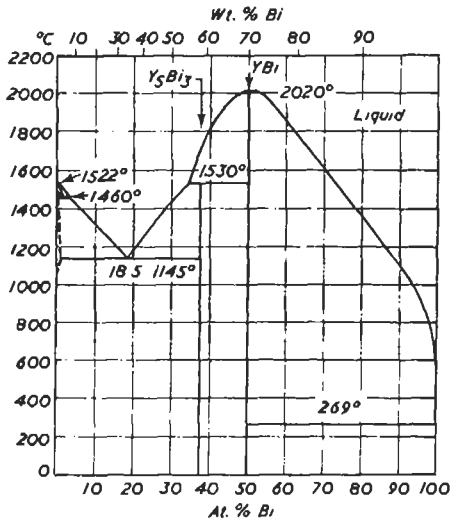
Bi–Tl



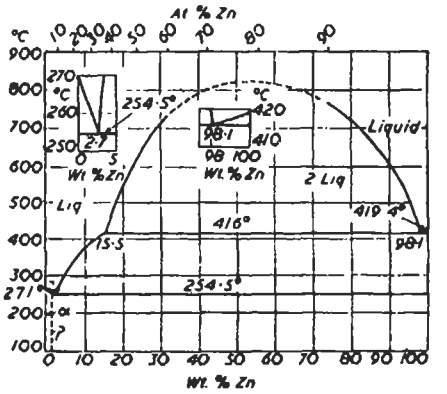
Bi–U



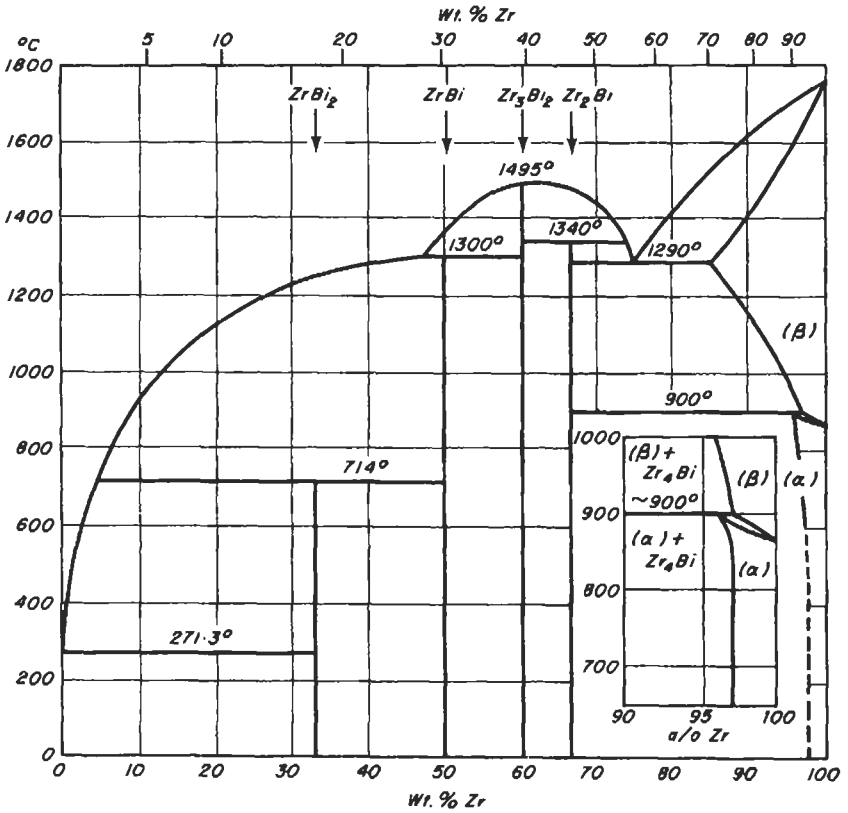
Bi–Y



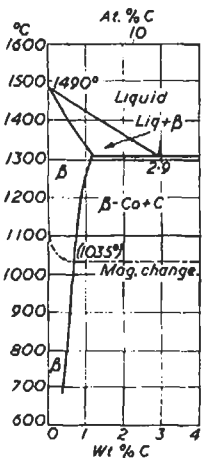
Bi–Zn



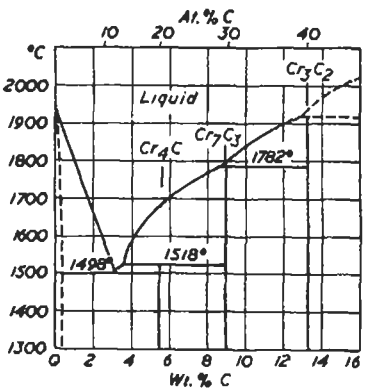
Bi–Zr


Wt. % Zr
°C
ZrBi2
ZrBi
Zr3Bi2
Zr2Bi
1495°
1340°
1300°
1290°
(β)
900°
714°
271·3°
(β) + Zr4Bi ~900°
(α) + Zr4Bi
(α)
a/o Zr
Wt. % Zr

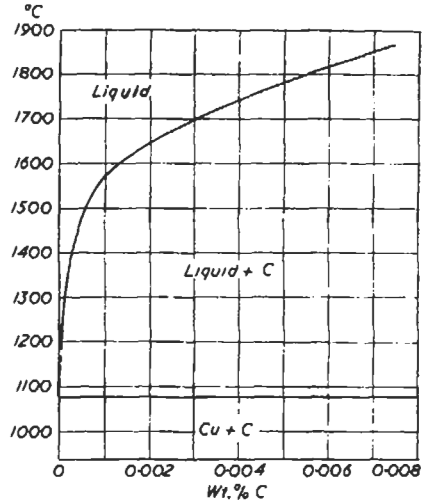
C–Co


At. % C
°C
1490°
Liquid
Liq+β
2·9
β
β-Co+C
1035°
Mag. change
Wt % C

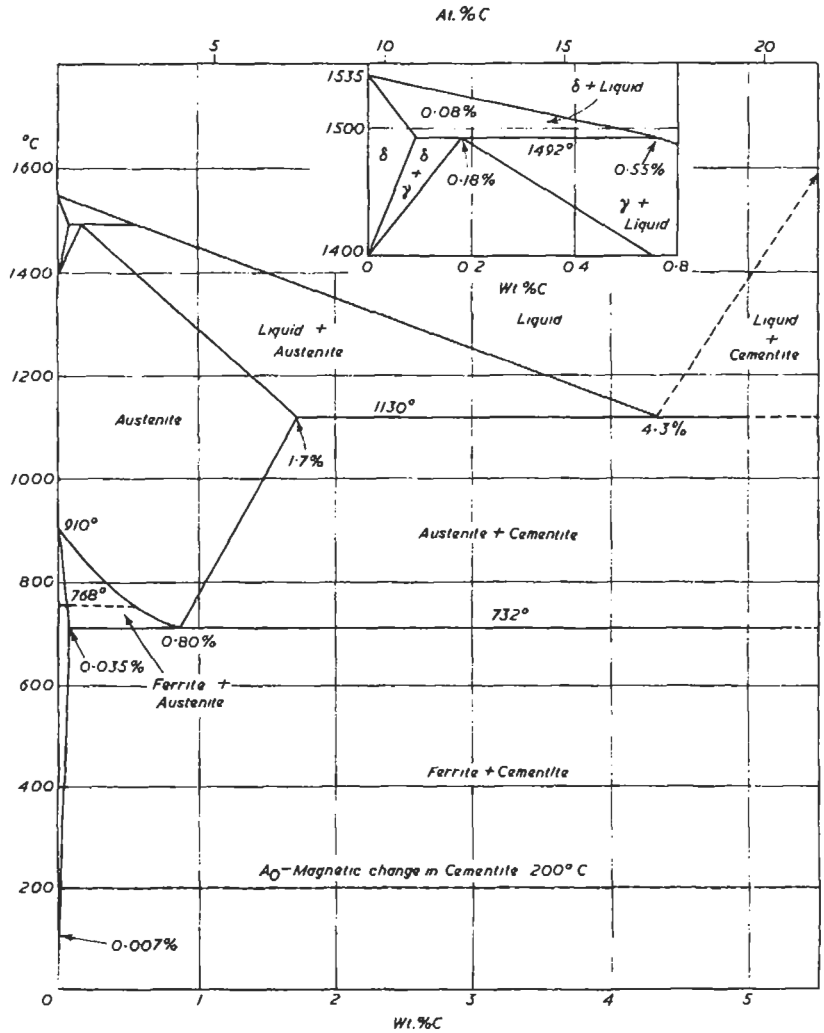
C–Cr


At. % C
°C
Liquid
Cr3C2
Cr7C3
Cr4C
1782°
1518°
1498°
Wt. % C

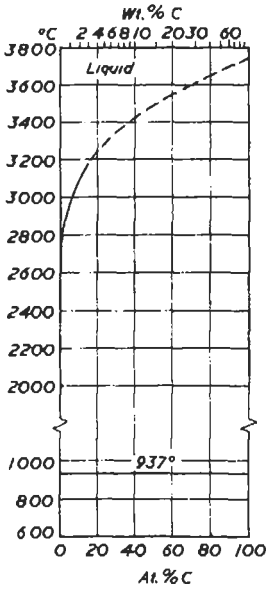
C–Cu


°C
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Liquid
Liquid + C
Cu + C
0
0·002
0·004
0·006
0·008
Wt.% C

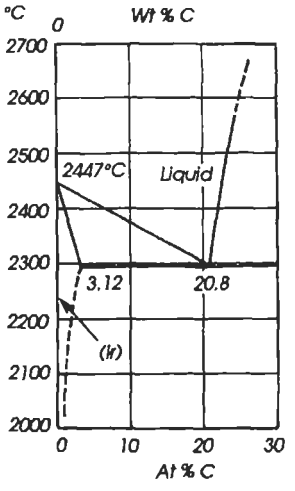
C–Fe


At.% C
5
10
15
20
°C
1600
1400
1200
1000
800
600
400
200
0
1
2
3
4
5
Wt.%C
1535
1500
1400
δ + Liquid
0·08%
δ
δ + γ
γ
0·18%
1492°
0·55%
γ + Liquid
0
0·2
0·4
0·8
Wt %C
Liquid
Liquid + Austenite
Liquid + Cementite
Austenite
1130°
4·3%
1·7%
910°
Austenite + Cementite
768°
732°
0·80%
0·035%
Ferrite + Austenite
Ferrite + Cementite
A0 – Magnetic change in Cementite 200° C
0·007%

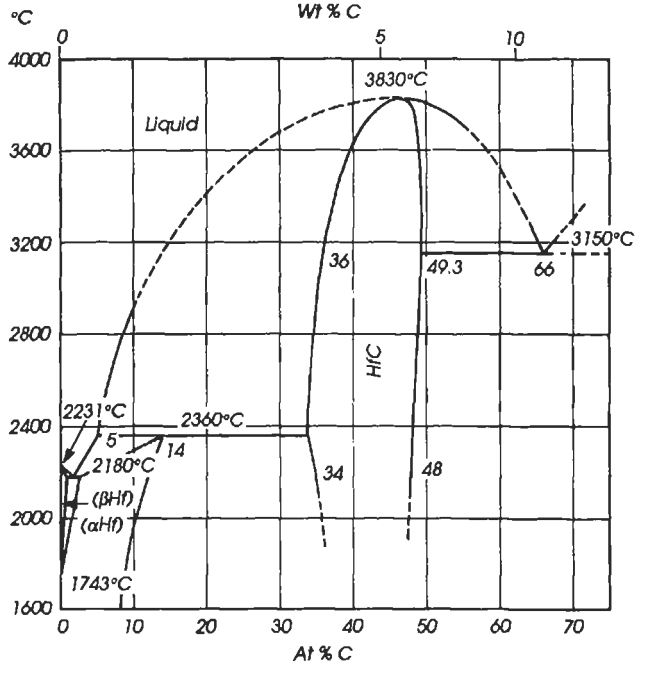
C–Ge


Wt. % C
°C 2 4 6 8 10 20 30 60
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1000
800
600
Liquid
937°
0 20 40 60 80 100
At. % C

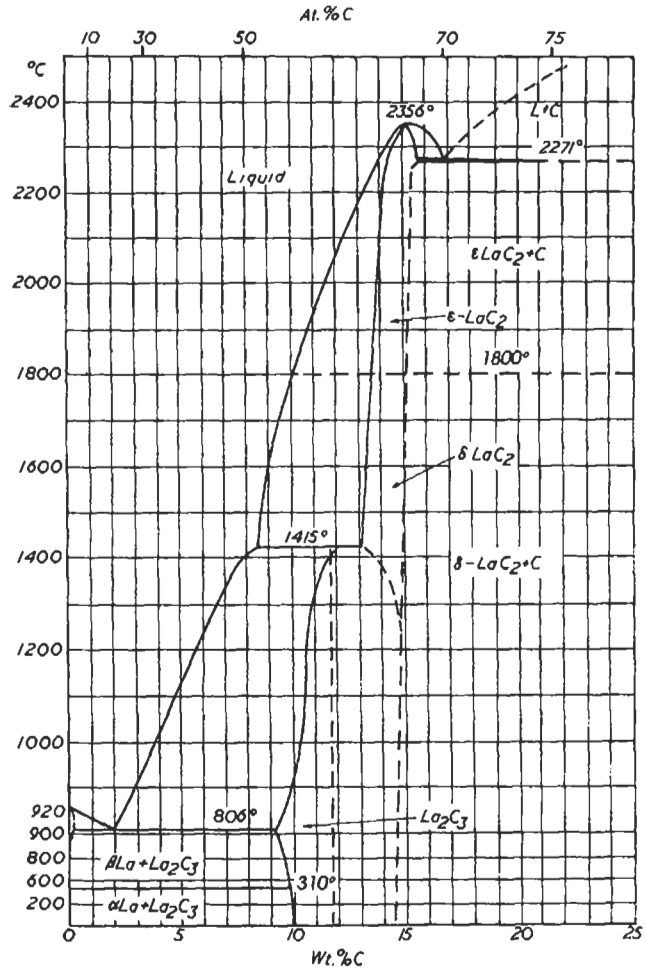
C–Ir


°C
Wt % C
0
2700
2600
2500
2400
2300
2200
2100
2000
2447°C
Liquid
3.12
20.8
(Ir)
0 10 20 30
At % C

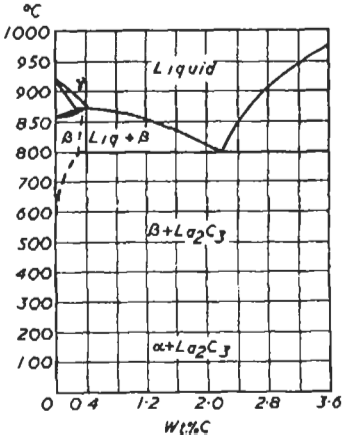
C–Hf


°C
Wt % C
0
5
10
4000
3600
3200
2800
2400
2000
1600
3830°C
Liquid
3150°C
36
49.3
66
HfC
2231°C
2360°C
5
14
2180°C
(βHf)
(αHf)
34
48
1743°C
0 10 20 30 40 50 60 70
At % C

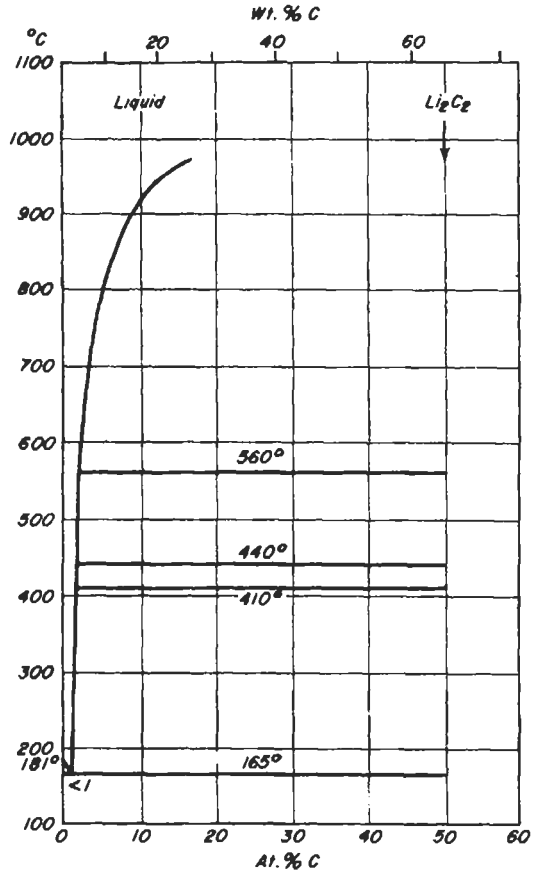
C–La


At.%C
10
30
50
70
75
°C
2400
2200
2000
1800
1600
1400
1200
1000
920
900
800
600
200
2356°
L+C
2271°
Liquid
εLaC2+C
ε-LaC2
1800°
δ LaC2
1415°
δ-LaC2+C
806°
La2C3
βLa+La2C3
310°
αLa+La2C3
0
5
10
15
20
25
Wt.%C

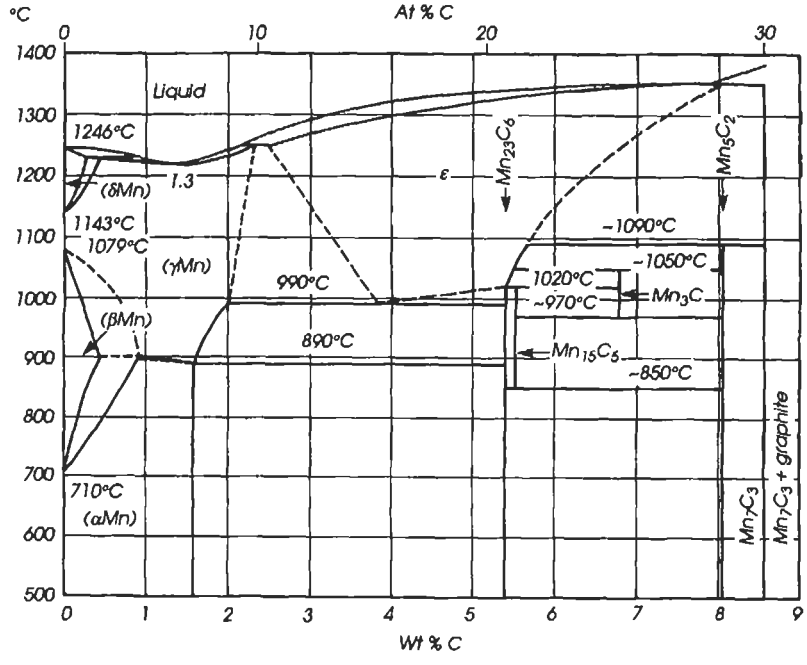
C–La


°C
1000
950
900
850
800
700
600
500
400
300
200
100
Liquid
β'
Liq+β
β+La2C3
α+La2C3
0
0·4
1·2
2·0
2·8
3·6
Wt.%C

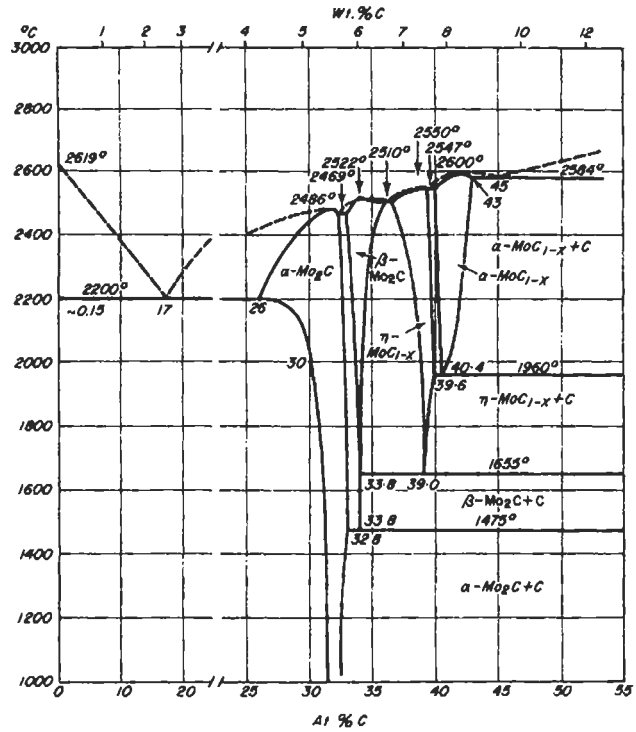
C–Li


Wt. % C
°C
20
40
60
1100
1000
900
800
700
600
500
400
300
200
100
Liquid
Li_2C_2
560°
440°
410°
165°
181°
<1
0
10
20
30
40
50
60
At. % C

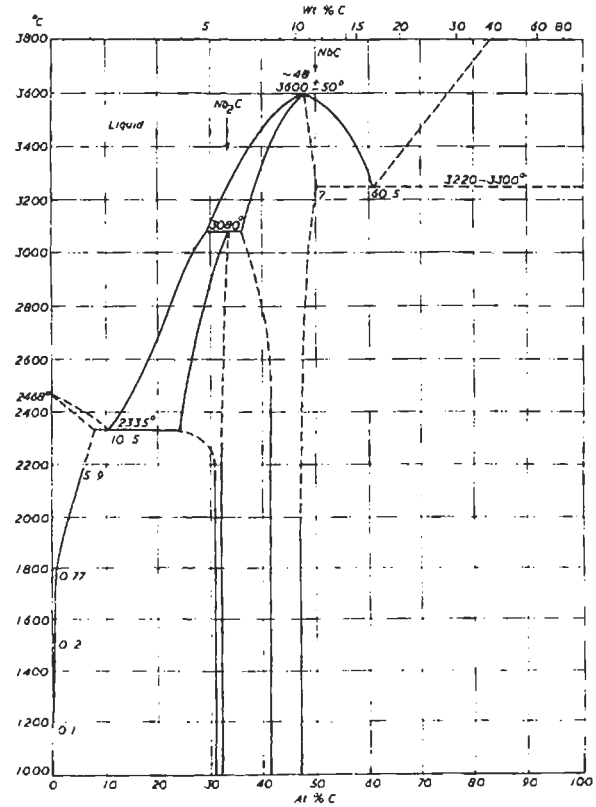
C–Mn


°C
At % C
0
10
20
30
1400
1300
1200
1100
1000
900
800
700
600
500
Liquid
1246°C
(δMn)
1.3
1143°C
1079°C
(γMn)
990°C
(βMn)
890°C
710°C
(αMn)
ε
$Mn_{23}C_6$
Mn_5C_2
~1090°C
~1050°C
1020°C
~970°C
Mn_3C
$Mn_{15}C_5$
~850°C
Mn_7C_3
Mn_7C_3 + graphite
0
1
2
3
4
5
6
7
8
9
Wt % C

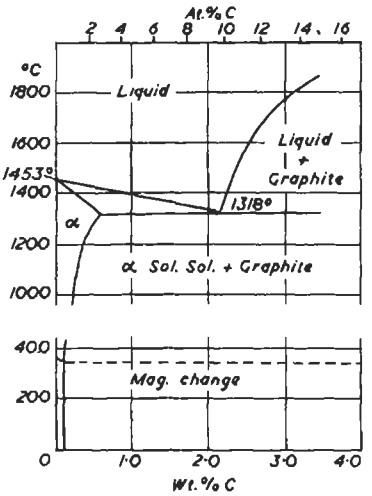
C–Mo


Wt. % C
°C
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
2619°
2522°
2510°
2550°
2547°
2600°
2564°
2469°
2486°
2200°
~0.15
17
26
30
45
43
40·4
39·6
1960°
1655°
33·8
39·0
33·8
32·8
1475°
α-Mo2C
β-Mo2C
η-MoC1-x
α-MoC1-x+C
α-MoC1-x
η-MoC1-x+C
β-Mo2C+C
α-Mo2C+C
At % C

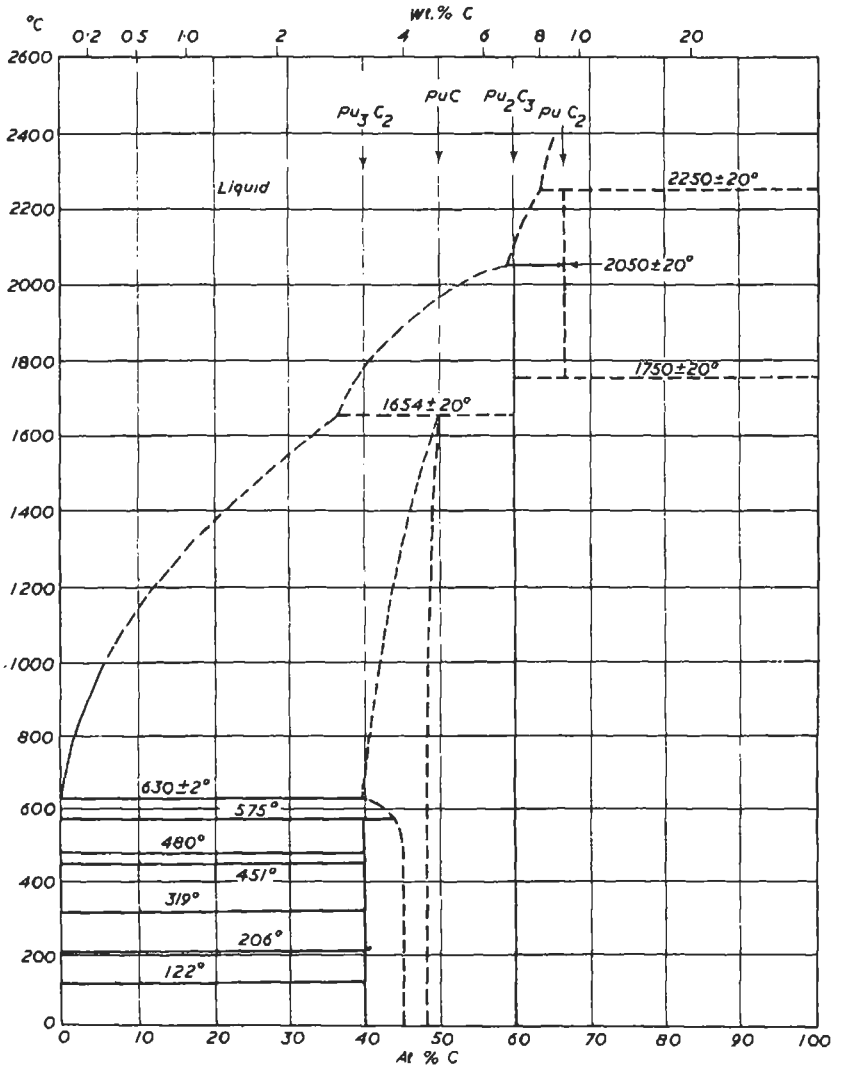
C–Nb


Wt % C
°C
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
NbC
~48
3600 ± 50°
Nb2C
Liquid
3220–3100°
60·5
3080°
2335°
10·5
5·9
0·77
0·2
0·1
At % C

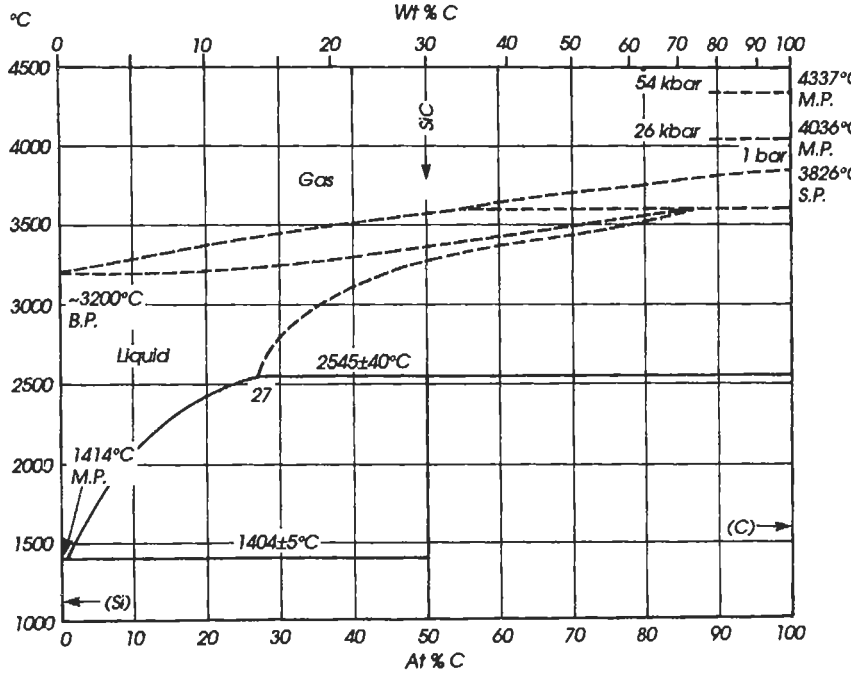
C–Ni


At.% C
2 4 6 8 10 12 14 16
°C
1800
1600
1453°
1400
1318°
1200
1000
Liquid
Liquid + Graphite
α
α Sol. Sol. + Graphite
400
200
0
Mag. change
1·0 2·0 3·0 4·0
Wt.% C

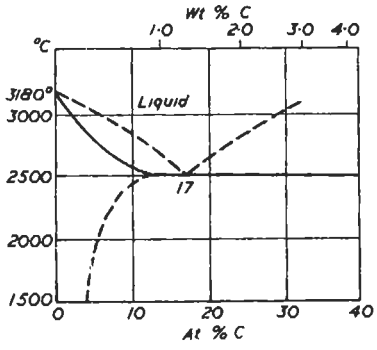
C–Pu


°C
Wt.% C
0·2 0·5 1·0 2 4 6 8 10 20
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Pu3C2
PuC
Pu2C3
Pu C2
Liquid
2250±20°
2050±20°
1750±20°
1654±20°
630±2°
575°
480°
451°
319°
206°
122°
0 10 20 30 40 50 60 70 80 90 100
At % C

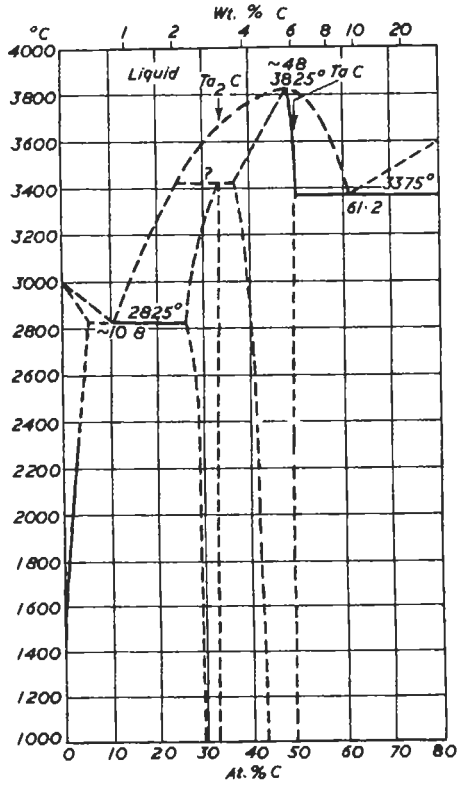
C–Si


°C
Wt % C
0 10 20 30 40 50 60 70 80 90 100
4500
4000
3500
3000
2500
2000
1500
1000
SiC
54 kbar
4337°C
M.P.
26 kbar
4036°C
M.P.
1 bar
3826°C
S.P.
Gas
~3200°C
B.P.
Liquid
2545±40°C
27
1414°C
M.P.
1404±5°C
(C)
(Si)
At % C

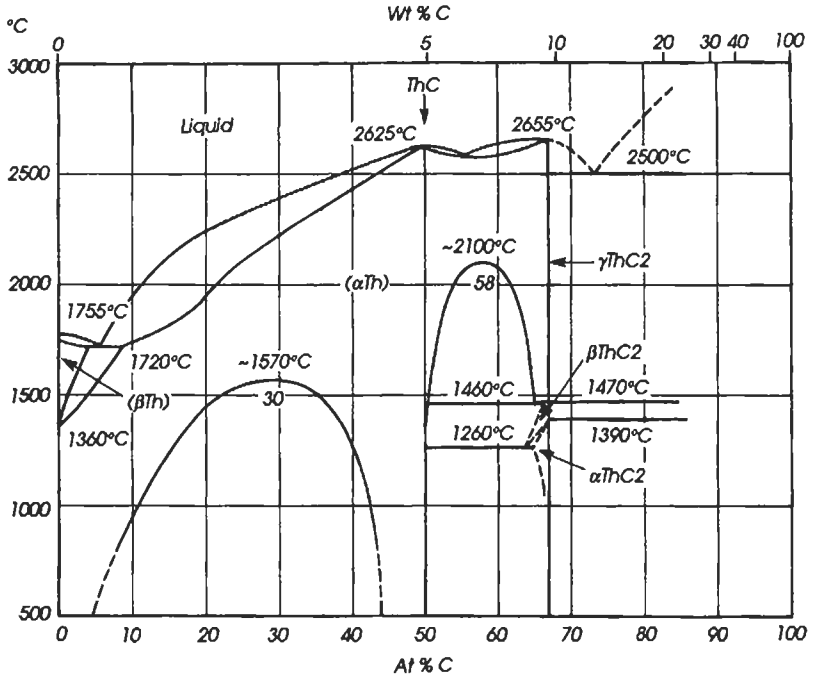
C–Re


°C
Wt % C
1·0 2·0 3·0 4·0
3180°
3000
2500
2000
1500
Liquid
17
0 10 20 30 40
At % C

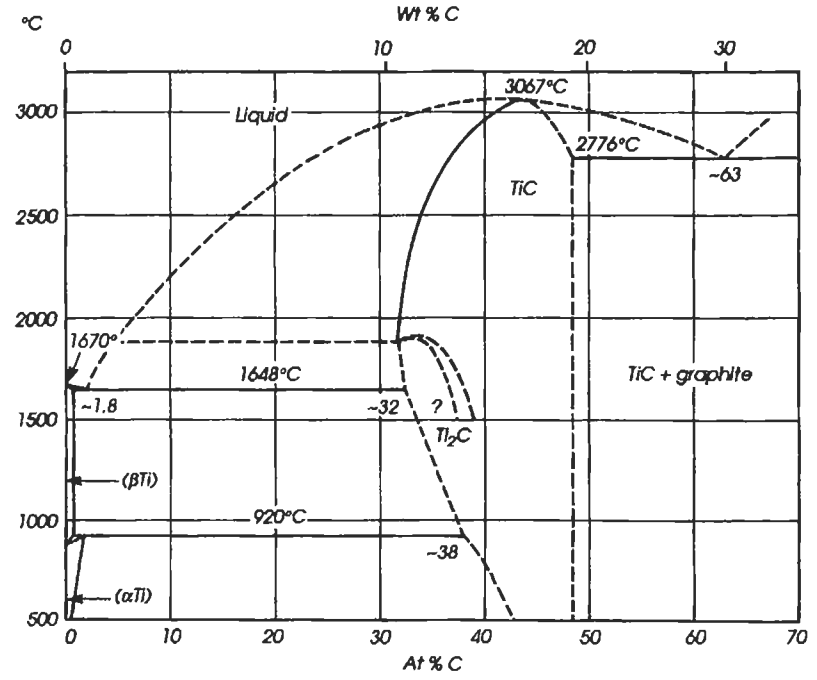
C–Ta


°C
Wt. % C
1 2 4 6 8 10 20
4000
3800
3600
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
Liquid
Ta2C
~48
3825° TaC
3375°
61·2
?
2825°
~10·8
0 10 20 30 40 50 60 70 80
At. % C

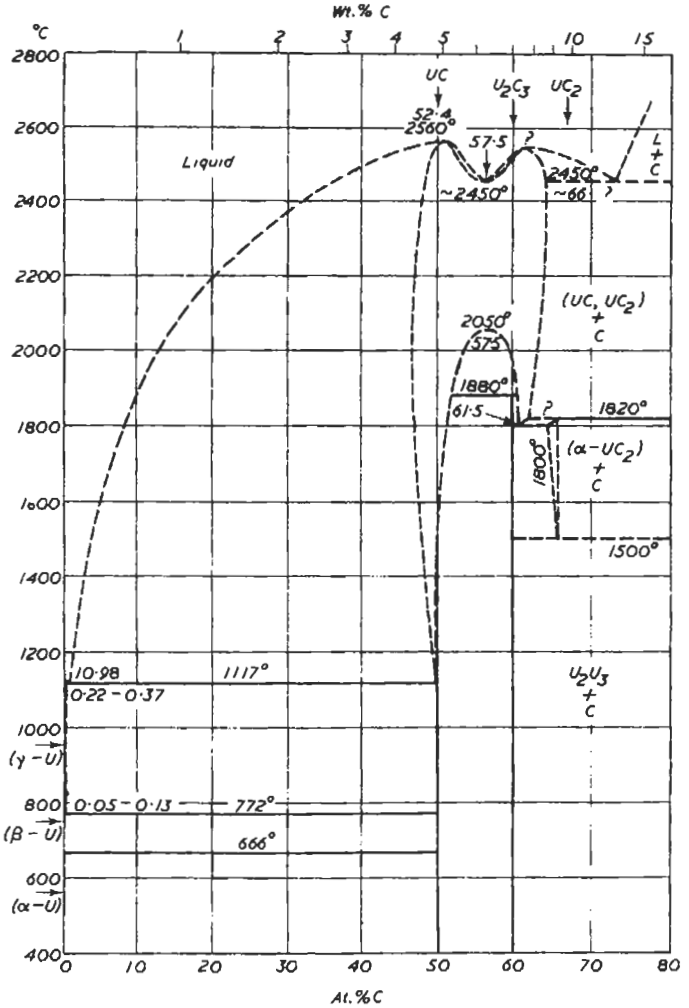
C–Th


°C
Wt % C
0
5
10
20
30
40
100
3000
2500
2000
1500
1000
500
Liquid
ThC
2625°C
2655°C
2500°C
~2100°C
γThC2
(αTh)
58
1755°C
1720°C
~1570°C
(βTh)
30
1460°C
1470°C
βThC2
1360°C
1260°C
1390°C
αThC2
0
10
20
30
40
50
60
70
80
90
100
At % C

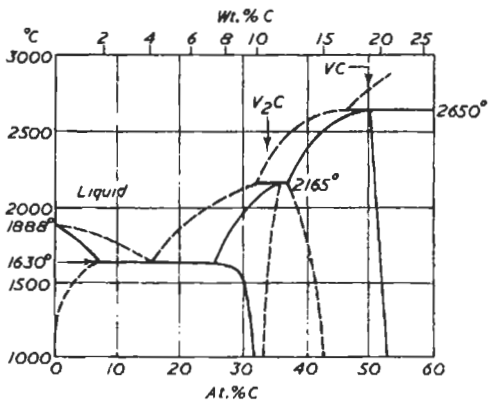
C–Ti


°C
Wt % C
0
10
20
30
3000
2500
2000
1500
1000
500
Liquid
3067°C
2776°C
~63
TiC
1670°
1648°C
TiC + graphite
~1.8
~32
?
Ti2C
(βTi)
920°C
~38
(αTi)
0
10
20
30
40
50
60
70
At % C

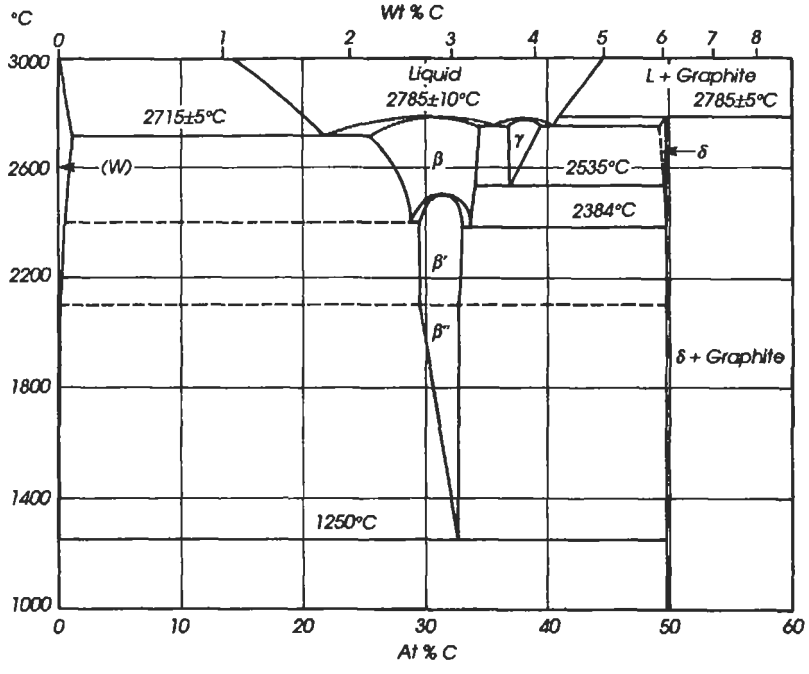
C–U


Wt.% C
°C
1
2
3
4
5
10
15
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
UC
U_2C_3
UC_2
52·4
2560°
57·5
~2450°
2450°
~66
Liquid
L + C
(UC, UC_2) + C
2050°
57·5
1880°
61·5
1820°
1800°
(α-UC_2) + C
1500°
10·98
1117°
0·22 - 0·37
U_2U_3 + C
(γ-U)
0·05 - 0·13
772°
(β-U)
666°
(α-U)
0
10
20
30
40
50
60
70
80
At.%C

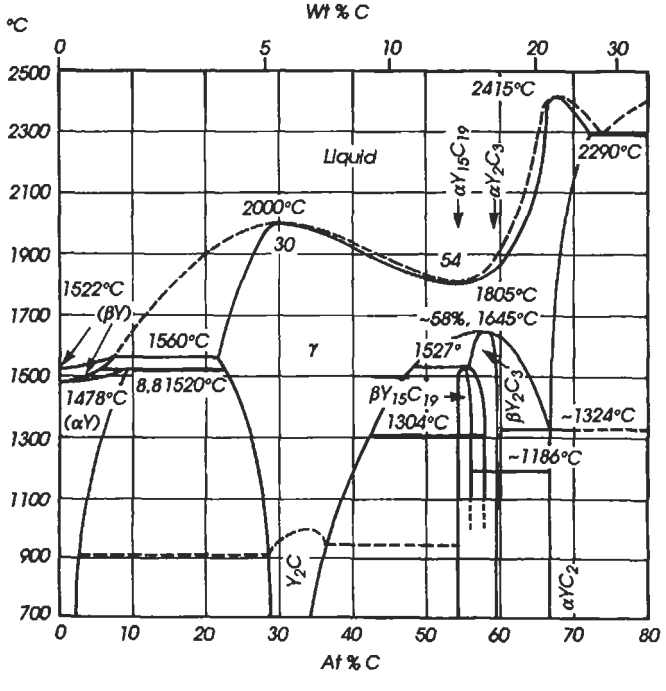
C–V

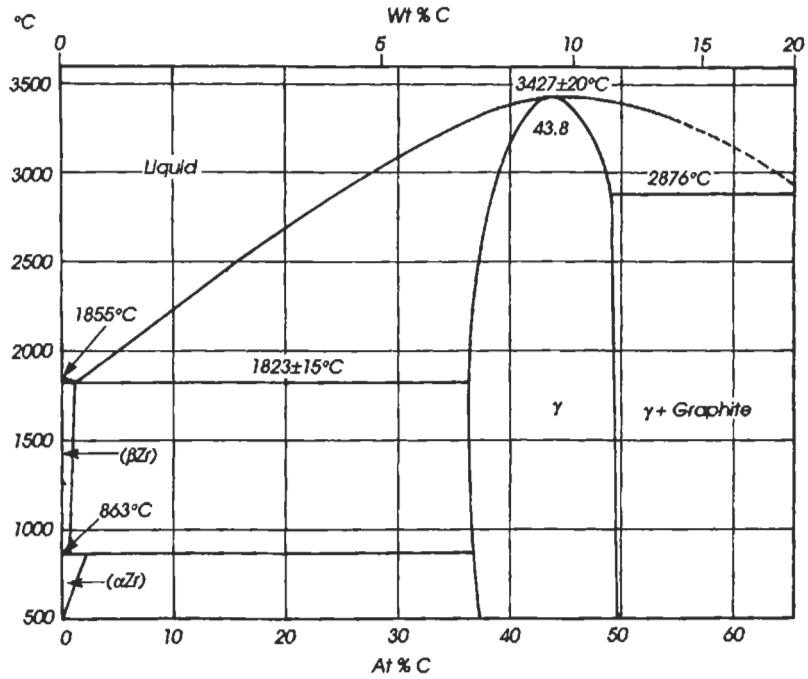

Wt.% C
°C
2
4
6
8
10
15
20
25
3000
2500
2000
1888°
1630°
1500
1000
VC
V_2C
2650°
2165°
Liquid
0
10
20
30
40
50
60
At.%C

C–W

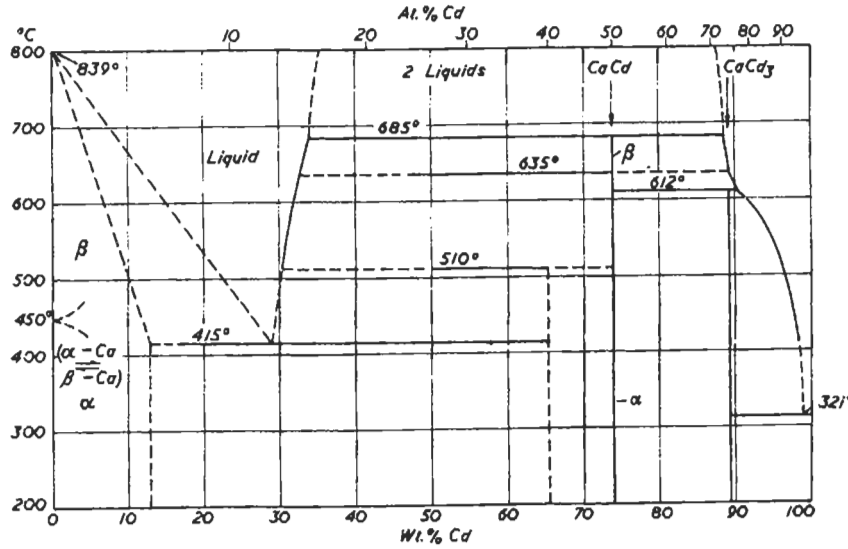

°C
Wt % C
0
1
2
3
4
5
6
7
8
3000
2600
2200
1800
1400
1000
Liquid
2785±10°C
L + Graphite
2785±5°C
2715±5°C
γ
δ
(W)
β
2535°C
2384°C
β'
β''
δ + Graphite
1250°C
0
10
20
30
40
50
60
At % C

C–Y


°C
Wt % C
0
5
10
20
30
2500
2300
2100
1900
1700
1600
1300
1100
900
700
2415°C
Liquid
αY15C19
αY2C3
2290°C
2000°C
30
54
1805°C
1522°C
(βY)
~58%, 1645°C
1560°C
γ
1527°
1478°C
(αY)
8,81520°C
βY15C19
1304°C
βY2C3
~1324°C
~1186°C
Y2C
αYC2
0
10
20
30
40
50
60
70
80
At % C

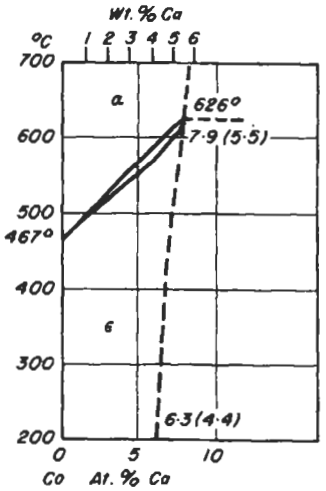

°C
Wt % C
0
5
10
15
20
3500
3000
2500
2000
1500
1000
500
3427±20°C
43.8
Liquid
2876°C
1855°C
1823±15°C
γ
γ + Graphite
(βZr)
863°C
(αZr)
0
10
20
30
40
50
60
At % C

C–Zr

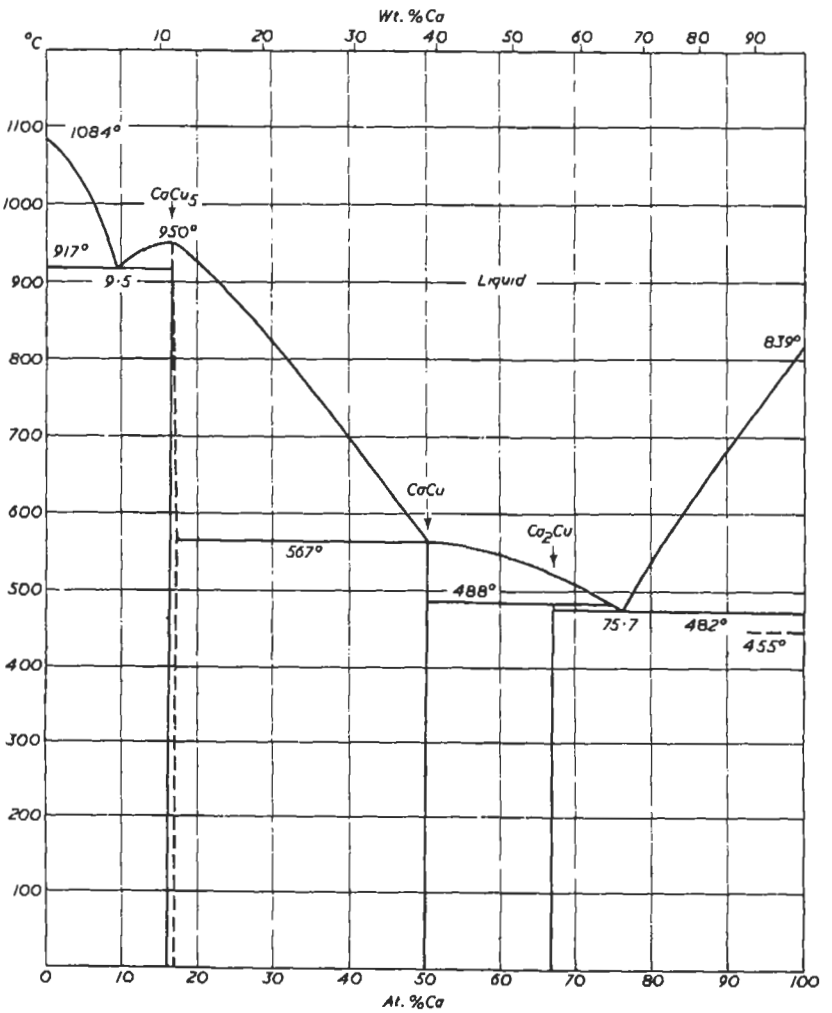

At. % Cd
°C
10
20
30
40
50
60
70
80
90
800
700
600
500
450°
400
300
200
839°
2 Liquids
CaCd
CaCd3
685°
Liquid
635°
β
612°
β
510°
415°
(α − Ca
β ⇌ Ca)
α
α
321°
0
10
20
30
40
50
60
70
80
90
100
Wt. % Cd

Ca–Cd

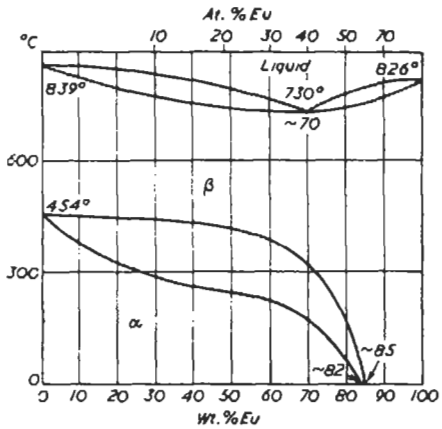
Ca–Co


Wt. % Ca
°C
1 2 3 4 5 6
700
600
500
467°
400
300
200
α
686°
7·9 (5·5)
6
6·3 (4·4)
0 5 10
Co At. % Ca

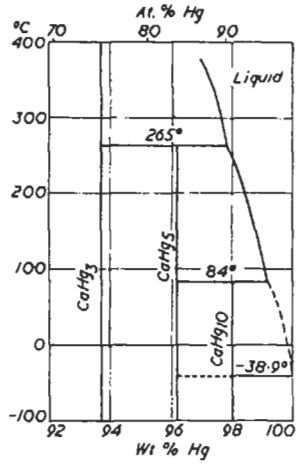
Ca–Cu


Wt. % Ca
°C
10 20 30 40 50 60 70 80 90
1100
1084°
1000
CaCu5
950°
917°
900
9·5
Liquid
839°
800
700
CaCu
600
Ca2Cu
567°
500
488°
75·7
482°
455°
400
300
200
100
0 10 20 30 40 50 60 70 80 90 100
At. % Ca

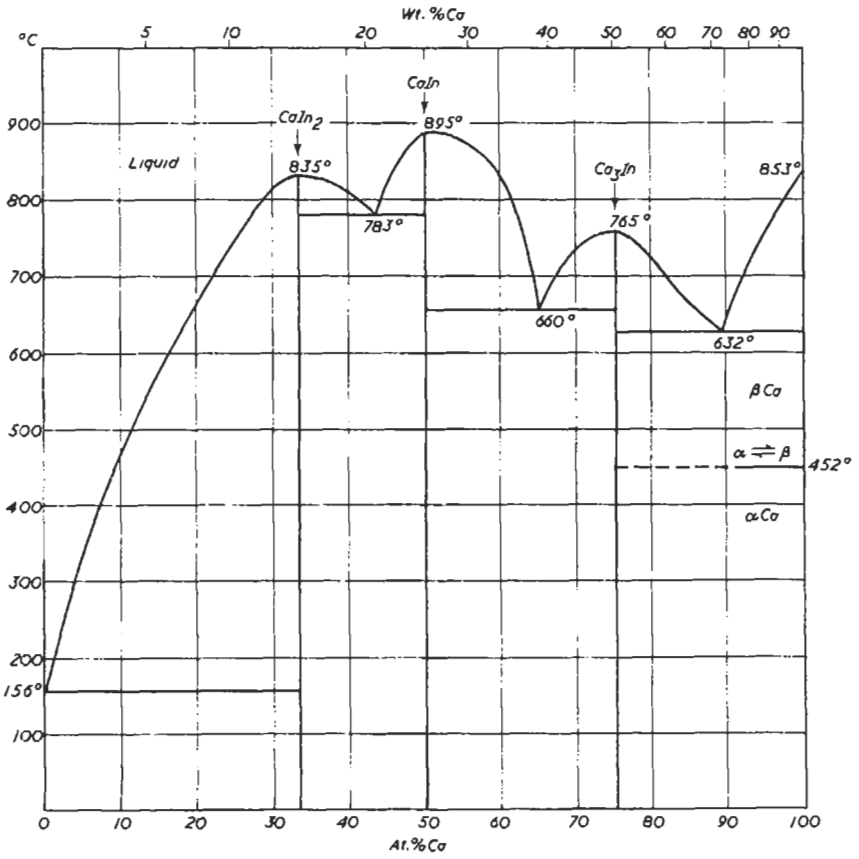
Ca–Eu



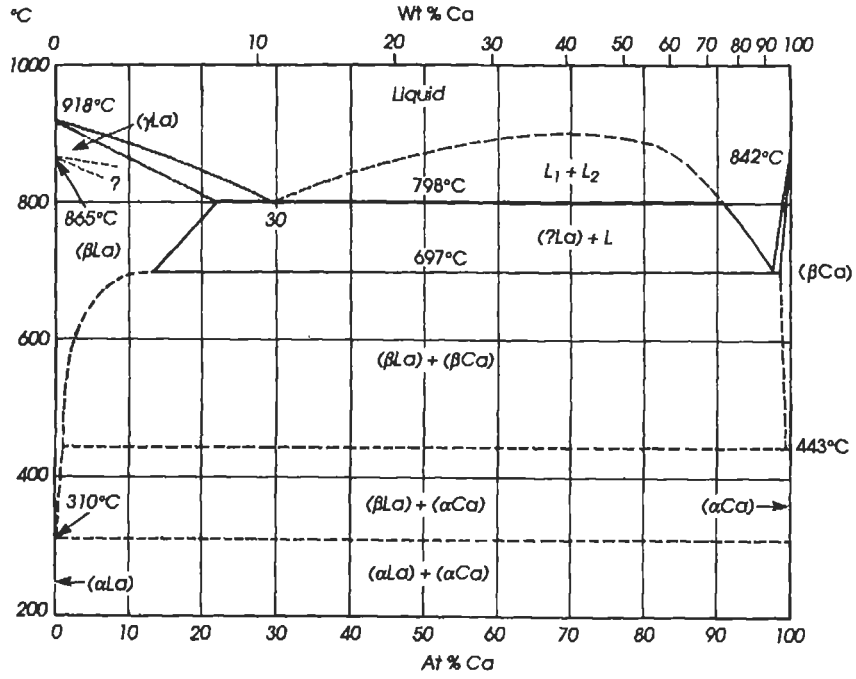
Ca–Hg



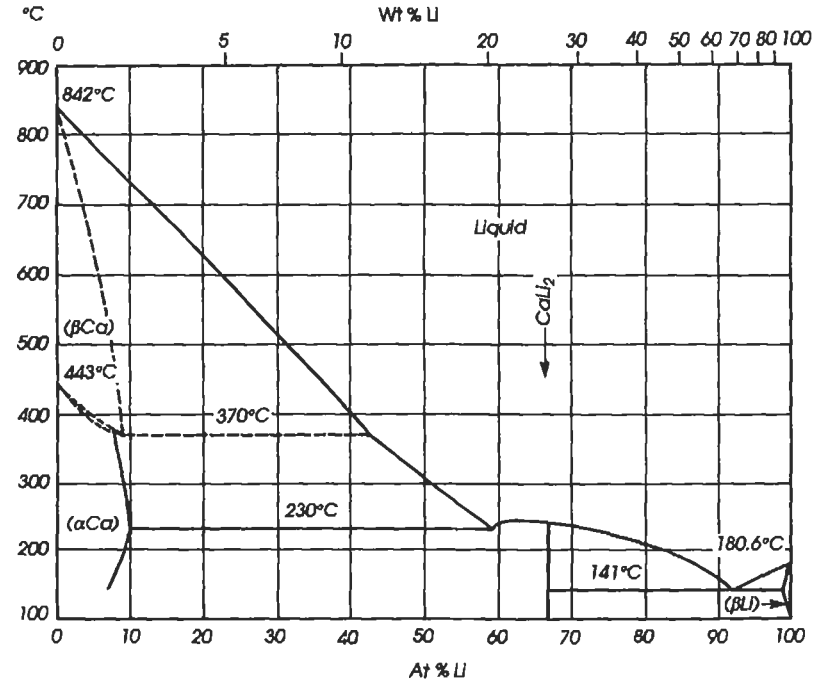
Ca–In



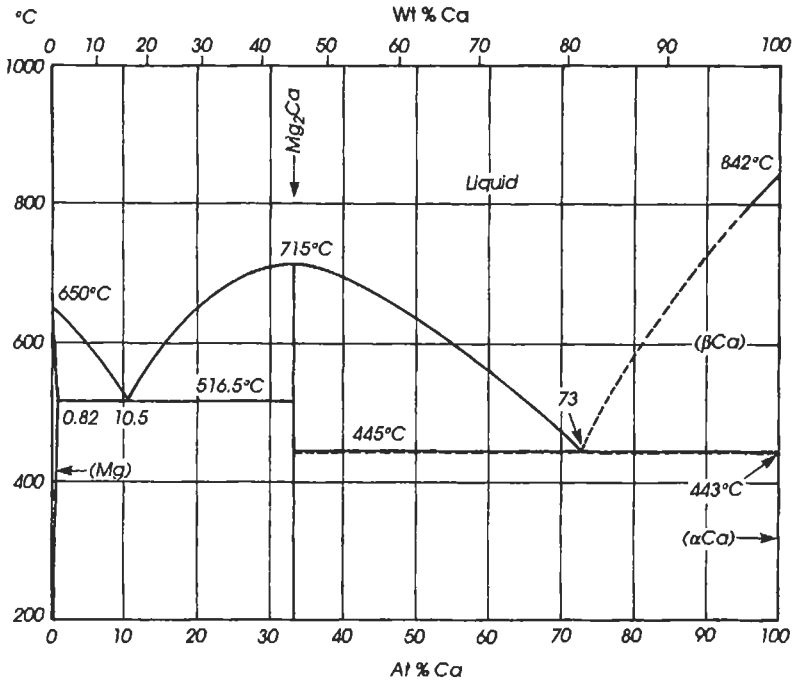
Ca–La


°C
Wt % Ca
0 10 20 30 40 50 60 70 80 90 100
1000
800
600
400
200
Liquid
918°C
(γLa)
?
865°C
(βLa)
30
798°C
L1 + L2
842°C
697°C
(?La) + L
(βCa)
(βLa) + (βCa)
443°C
310°C
(βLa) + (αCa)
(αCa)
(αLa)
(αLa) + (αCa)
0 10 20 30 40 50 60 70 80 90 100
At % Ca

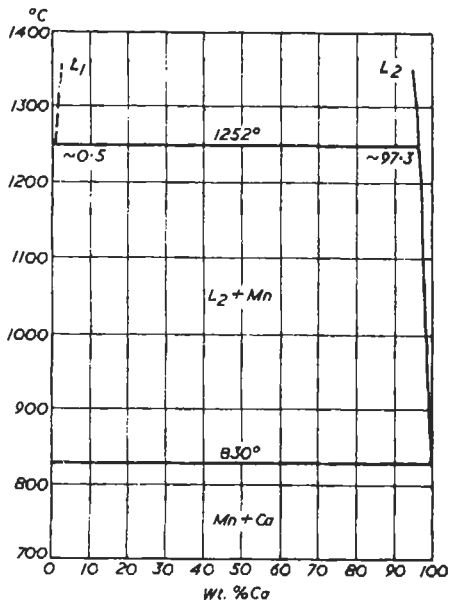
Ca–Li


°C
Wt % Li
0 5 10 20 30 40 50 60 70 80 100
900
800
700
600
500
400
300
200
100
842°C
Liquid
CaLi2
(βCa)
443°C
370°C
230°C
(αCa)
180.6°C
141°C
(βLi)
0 10 20 30 40 50 60 70 80 90 100
At % Li

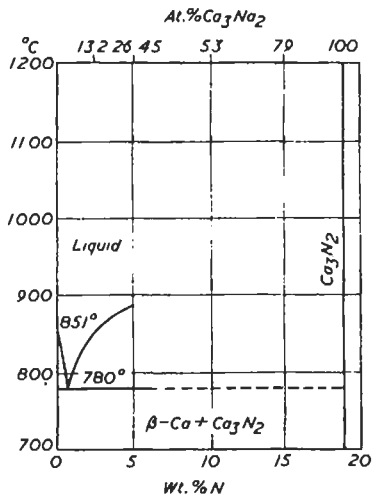
Ca–Mg



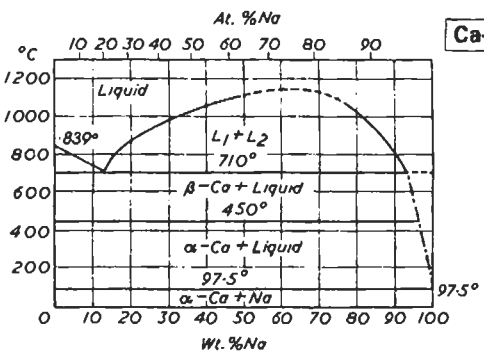
Ca–Mn



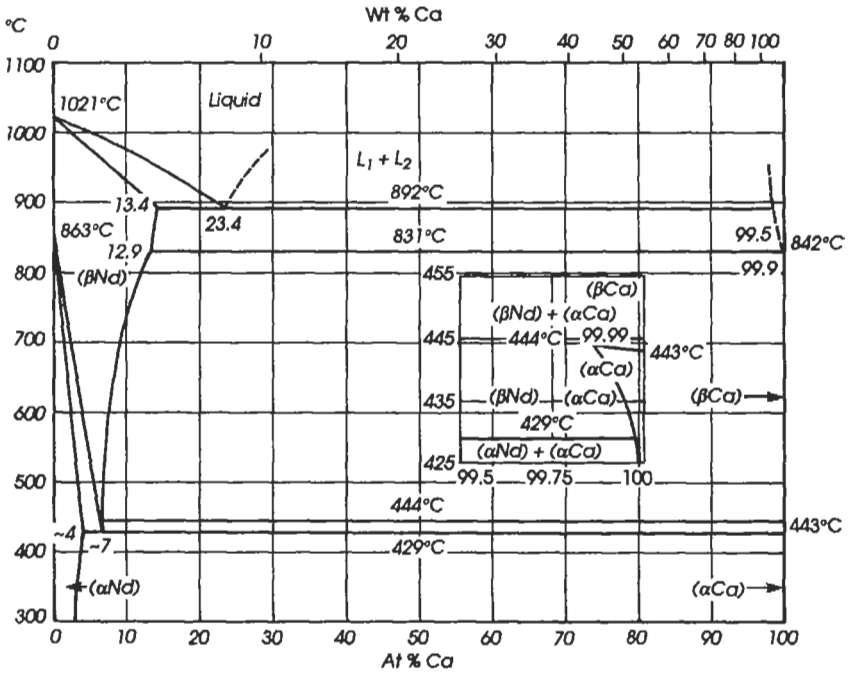
Ca–N



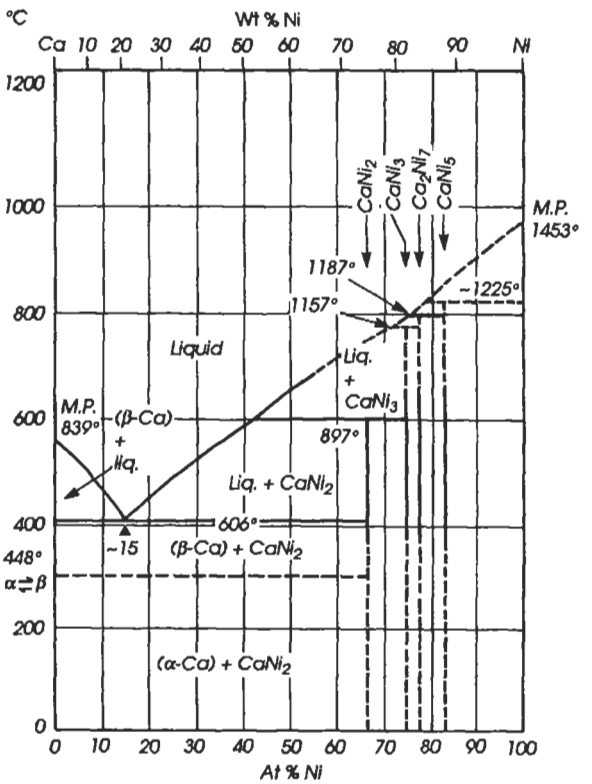
Ca–Na



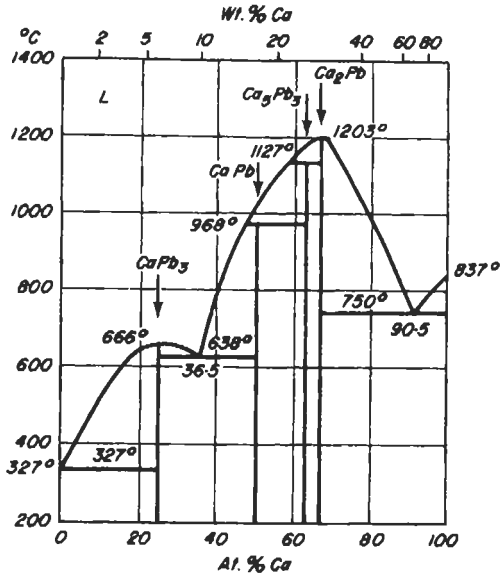
Ca–Nd


°C
Wt % Ca
0 10 20 30 40 50 60 70 80 100
1100
1000
900
800
700
600
500
400
300
1021°C
Liquid
$L_1 + L_2$
892°C
13.4
23.4
863°C
12.9
(βNd)
831°C
99.5
842°C
99.9
455
(βCa)
(βNd) + (αCa)
445
444°C
99.99
443°C
(αCa)
435
(βNd)
(αCa)
(βCa)
429°C
(αNd) + (αCa)
425
99.5
99.75
100
444°C
443°C
~4
~7
429°C
(αNd)
(αCa)
0 10 20 30 40 50 60 70 80 90 100
At % Ca

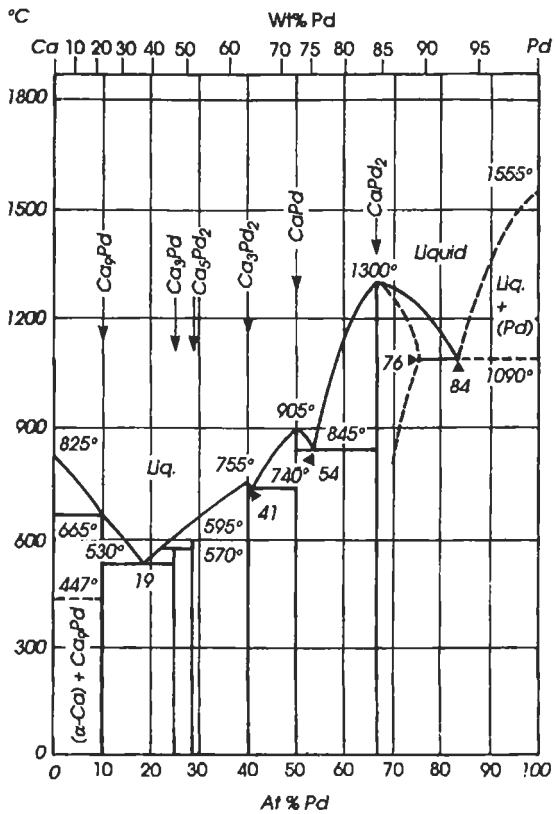
Ca–Ni


°C
Wt % Ni
Ca 10 20 30 40 50 60 70 80 90 Ni
1200
1000
800
600
400
448°
α⇄β
200
0
$CaNi_2$
$CaNi_3$
Ca_2Ni_7
$CaNi_5$
M.P.
1453°
1187°
~1225°
1157°
Liquid
Liq.
+
$CaNi_3$
M.P.
839°
(β-Ca)
+
liq.
897°
Liq. + $CaNi_2$
606°
~15
(β-Ca) + $CaNi_2$
(α-Ca) + $CaNi_2$
0 10 20 30 40 50 60 70 80 90 100
At % Ni

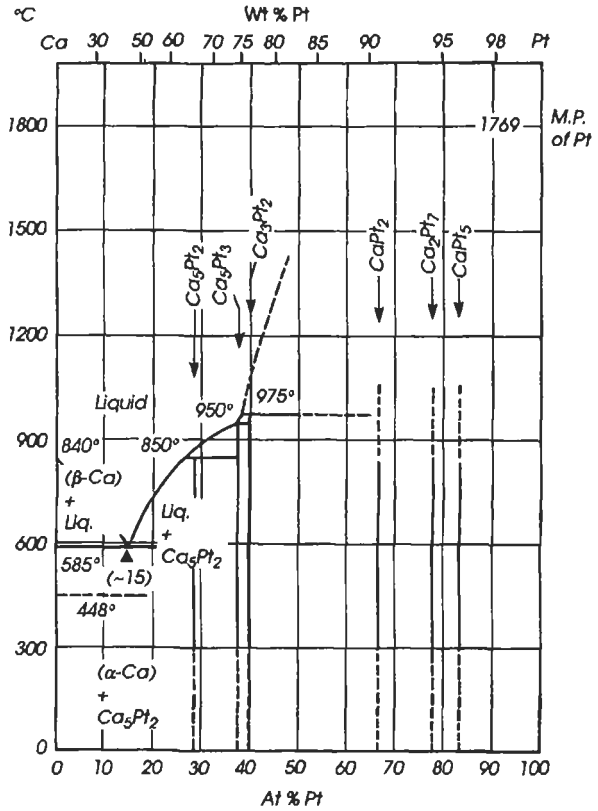
Ca–Pb


Wt. % Ca
°C
2
5
10
20
40
60 80
1400
1200
1000
800
600
400
327°
200
L
Ca_5Pb_3
Ca_2Pb
1205°
1127°
CaPb
968°
$CaPb_3$
837°
750°
90·5
666°
638°
36·5
327°
0
20
40
60
80
100
At. % Ca

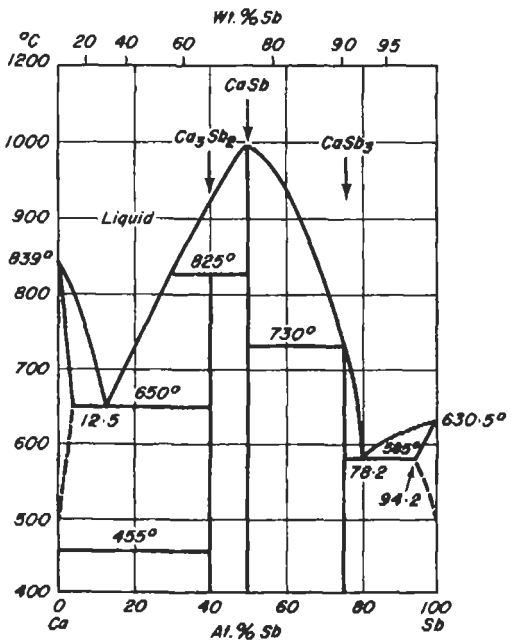
Ca–Pd


°C
Wt% Pd
Ca 10 20 30 40 50 60 70 75 80 85 90 95 Pd
1800
1500
1200
900
600
300
0
Ca_6Pd
Ca_3Pd
Ca_5Pd_2
Ca_3Pd_2
CaPd
$CaPd_2$
1555°
Liquid
1300°
Liq. + (Pd)
76
84
1090°
905°
845°
825°
Liq.
755°
740°
54
41
665°
530°
595°
570°
19
447°
(α-Ca) + Ca_6Pd
0
10
20
30
40
50
60
70
80
90
100
At % Pd

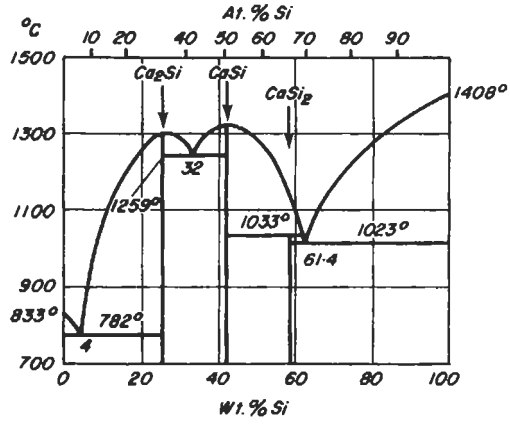
Ca–Pt


°C
Wt % Pt
Ca 30 50 60 70 75 80 85 90 95 98 Pt
1800
1500
1200
900
600
300
0
1769
M.P. of Pt
Ca_5Pt_2
Ca_5Pt_3
Ca_3Pt_2
$CaPt_2$
Ca_2Pt_7
$CaPt_5$
Liquid
950°
975°
840°
850°
(β-Ca) + Liq.
Liq. + Ca_5Pt_2
585°
(~15)
448°
(α-Ca) + Ca_5Pt_2
0 10 20 30 40 50 60 70 80 90 100
At % Pt

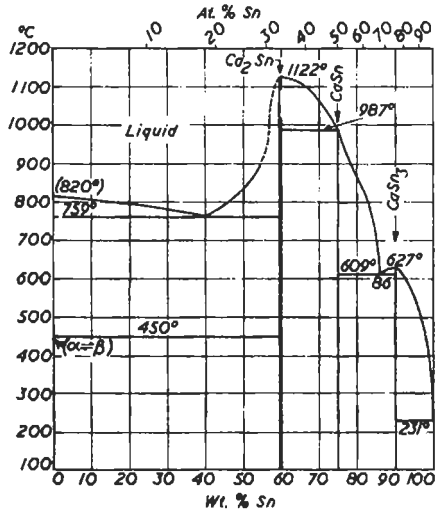
Ca–Sb


Wt. % Sb
°C
20 40 60 80 90 95
1200
1000
900
839°
800
700
600
500
400
CaSb
Ca_3Sb_2
$CaSb_3$
Liquid
825°
730°
650°
12·5
630·5°
585°
78·2
94·2
455°
0 20 40 60 80 100
Ca
At. % Sb
Sb

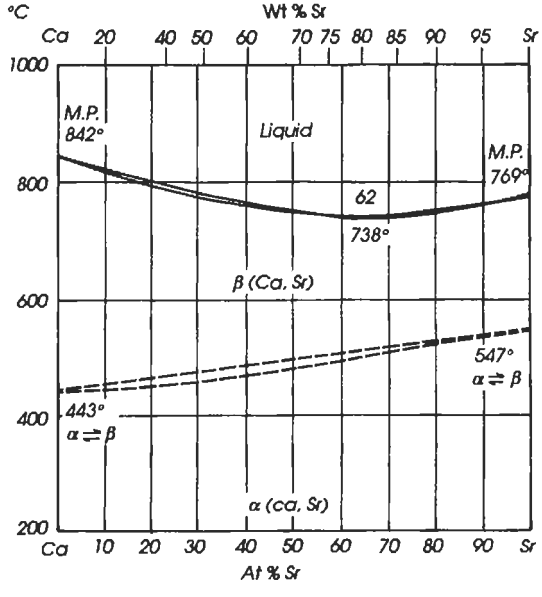
Ca–Si



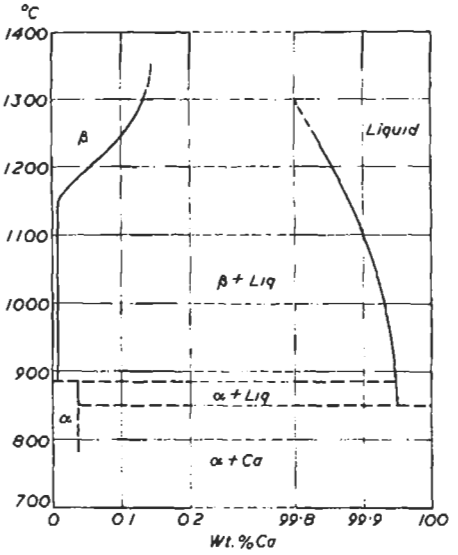
Ca–Sn



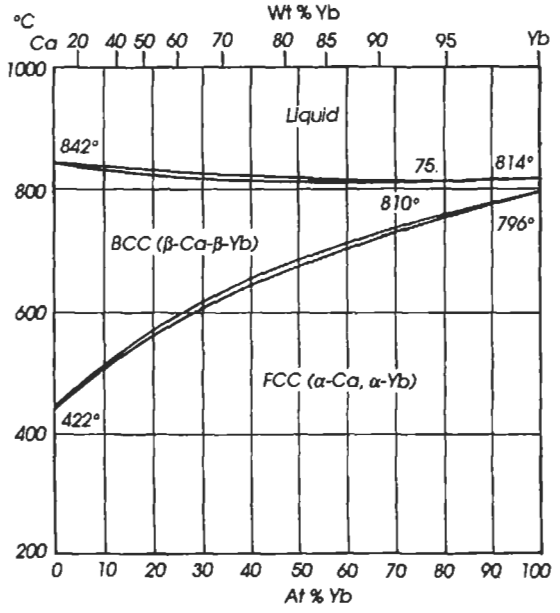
Ca–Sr



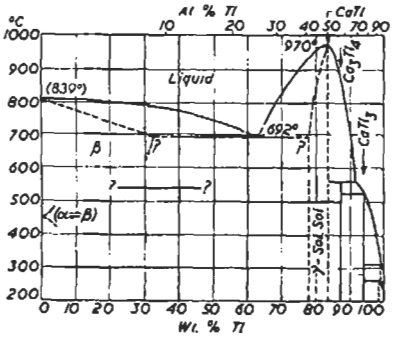
Ca–Ti



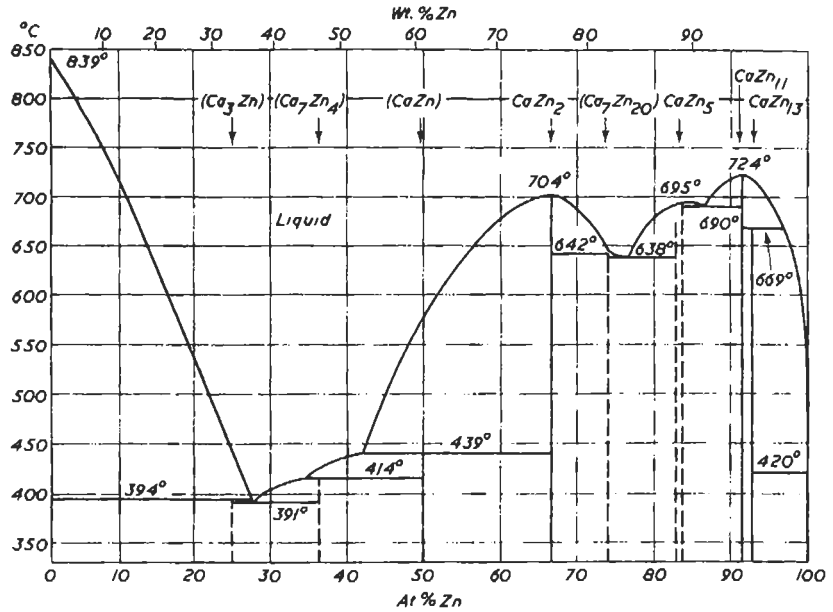
Ca–Yb



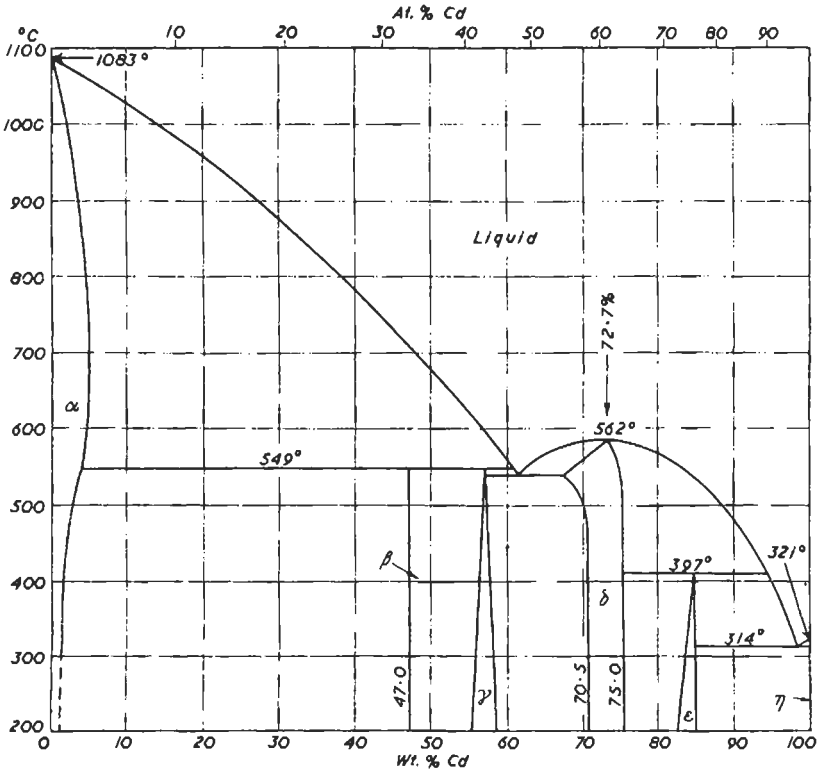
Ca–Tl



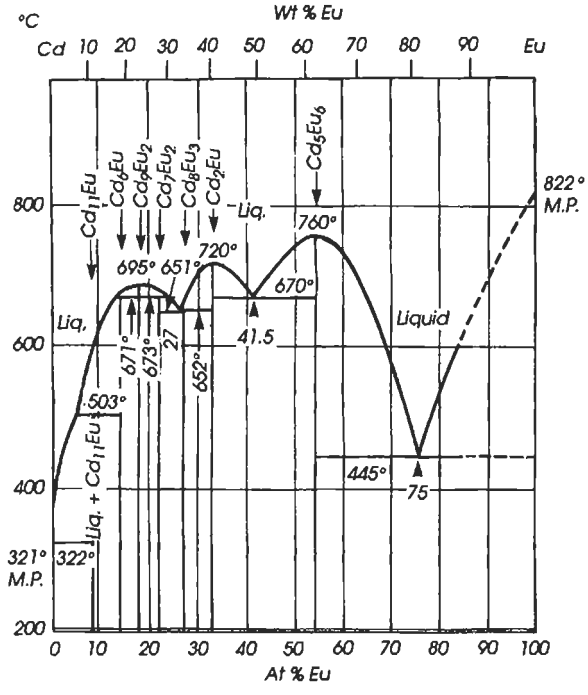
Ca–Zn


Wt. % Zn
°C
839°
(Ca3Zn)
(Ca7Zn4)
(CaZn)
CaZn2
(Ca7Zn20)
CaZn5
CaZn11
CaZn13
Liquid
704°
695°
724°
690°
642°
638°
669°
439°
414°
420°
394°
391°
At % Zn

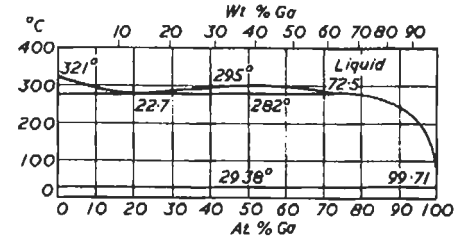
Cd–Cu


At. % Cd
°C
1083°
Liquid
72·7%
562°
549°
α
β
γ
δ
ε
η
397°
321°
314°
47·0
70·5
75·0
Wt. % Cd

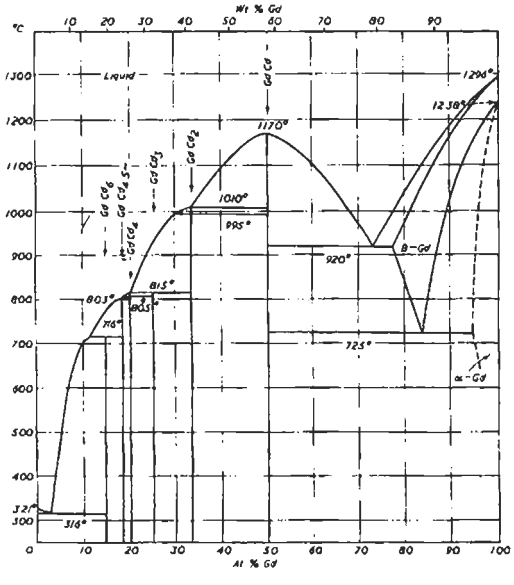
Cd–Eu



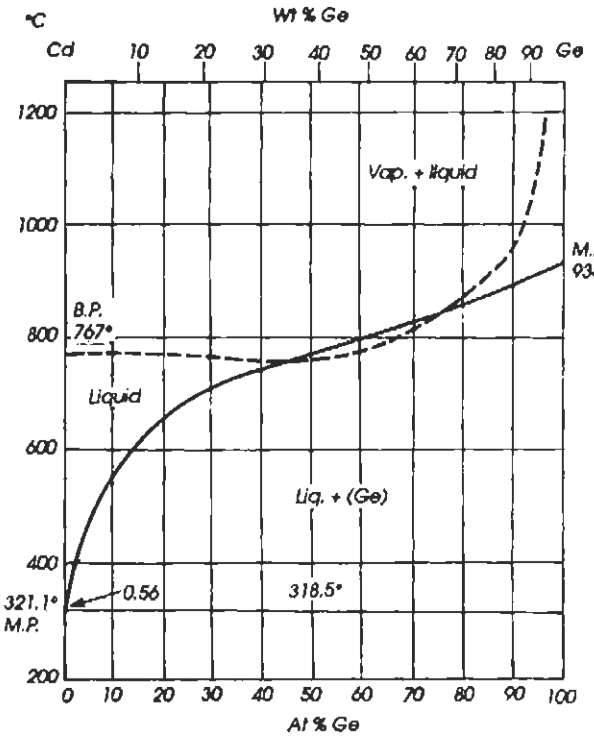
Cd–Ga



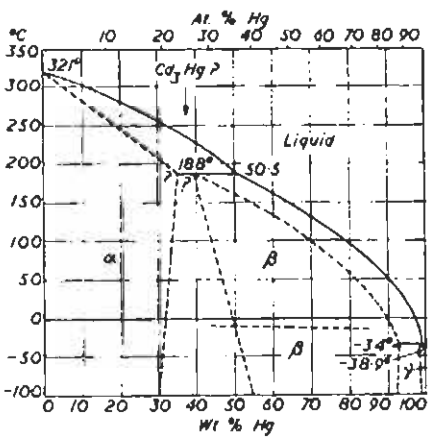
Cd–Gd



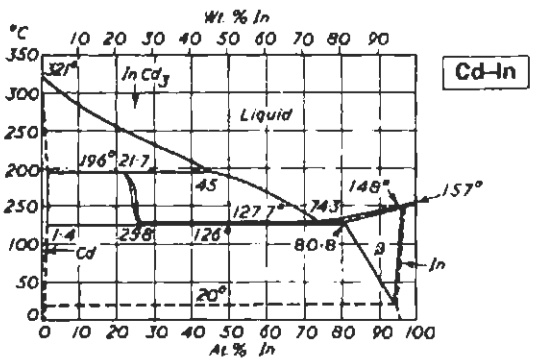
Cd–Ge



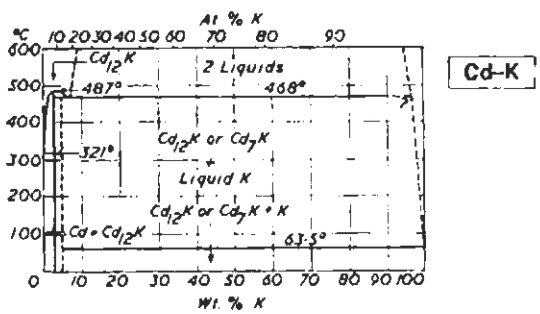
Cd–Hg



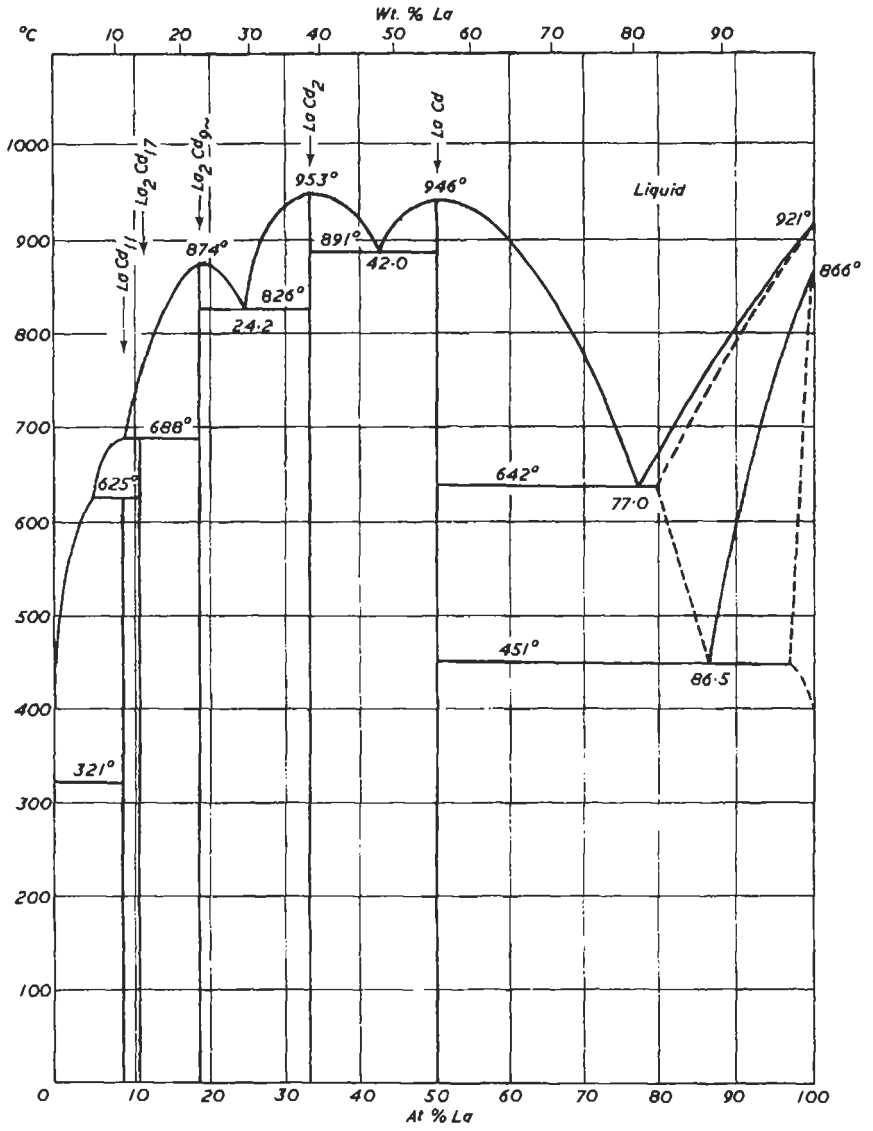
Cd–In



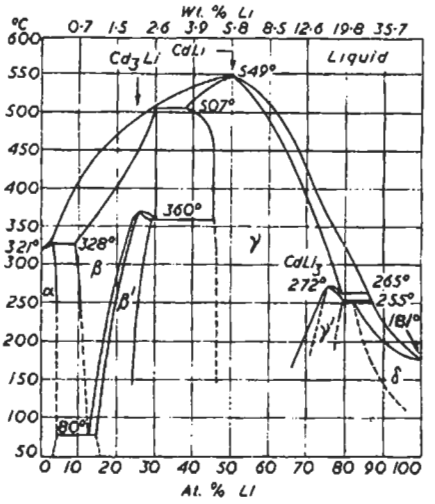
Cd–K



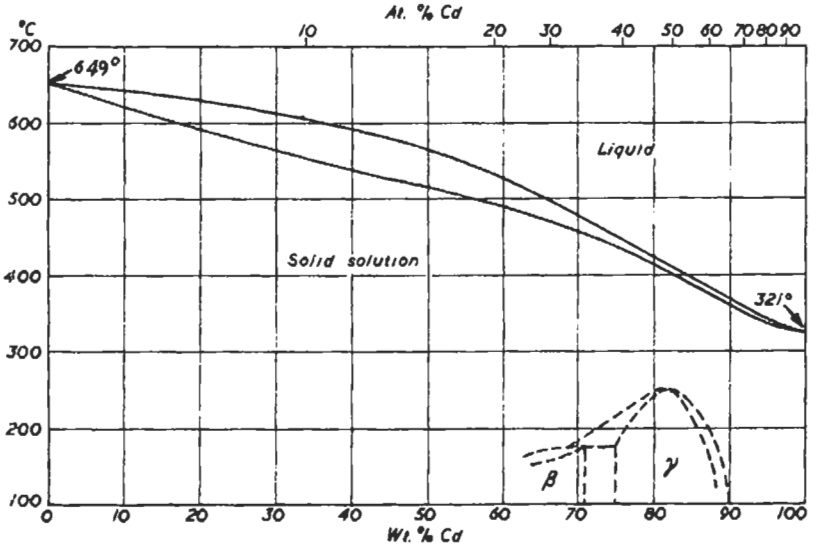
Cd–La


Wt. % La
°C
10
20
30
40
50
60
70
80
90
La Cd11
La2 Cd17
La2 Cd9~
La Cd2
La Cd
953°
946°
Liquid
921°
874°
891°
42·0
866°
826°
24·2
688°
625°
642°
77·0
451°
86·5
321°
1000
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
At % La

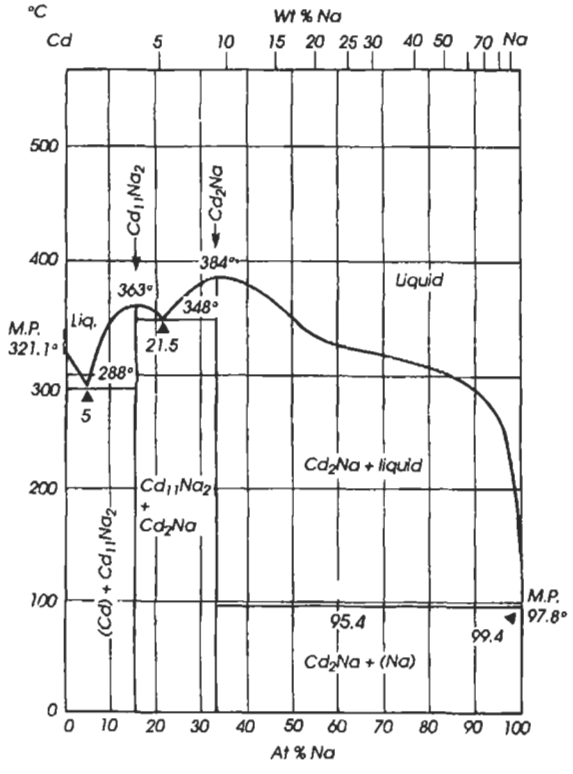
Cd–Li


°C
Wt. % Li
0·7 1·5 2·6 3·9 5·8 8·5 12·6 19·8 35·7
600
550
500
450
400
350
300
250
200
150
100
50
Cd3Li
CdLi
Liquid
549°
507°
360°
328°
321°
β
γ
α
β'
CdLi3
272°
265°
255°
δ
80°
0 10 20 30 40 50 60 70 80 90 100
At. % Li

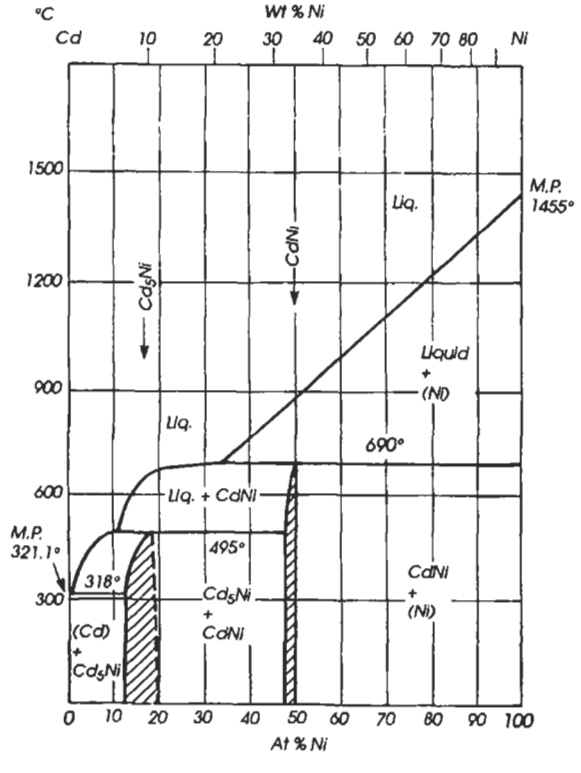
Cd–Mg


At. % Cd
°C
10 20 30 40 50 60 70 80 90
700
600
500
400
300
200
100
649°
Liquid
Solid solution
321°
β
γ
0 10 20 30 40 50 60 70 80 90 100
Wt. % Cd

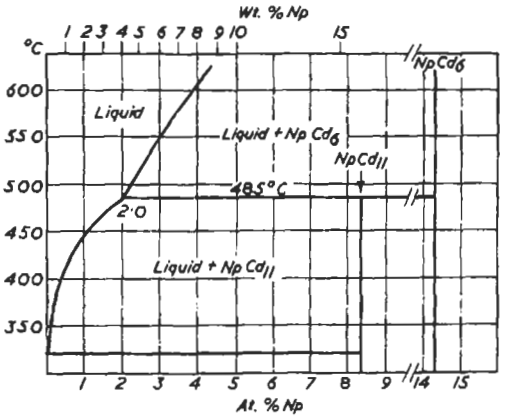
Cd–Na


°C
Wt % Na
Cd
5
10
15
20
25
30
40
50
70
Na
500
400
300
200
100
0
$Cd_{11}Na_2$
Cd_2Na
384°
363°
348°
Liquid
Liq.
M.P.
321.1°
21.5
288°
5
Cd_2Na + liquid
$Cd_{11}Na_2$
+
Cd_2Na
(Cd) + $Cd_{11}Na_2$
M.P.
97.8°
95.4
99.4
Cd_2Na + (Na)
0
10
20
30
40
50
60
70
80
90
100
At % Na

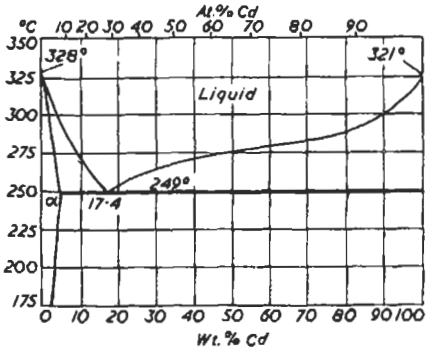
Cd–Ni


°C
Wt % Ni
Cd
10
20
30
40
50
60
70
80
Ni
1500
1200
900
600
300
Cd_5Ni
CdNi
Liq.
M.P.
1455°
Liquid
+
(Ni)
690°
Liq.
Liq. + CdNi
M.P.
321.1°
495°
318°
Cd_5Ni
+
CdNi
CdNi
+
(Ni)
(Cd)
+
Cd_5Ni
0
10
20
30
40
50
60
70
80
90
100
At % Ni

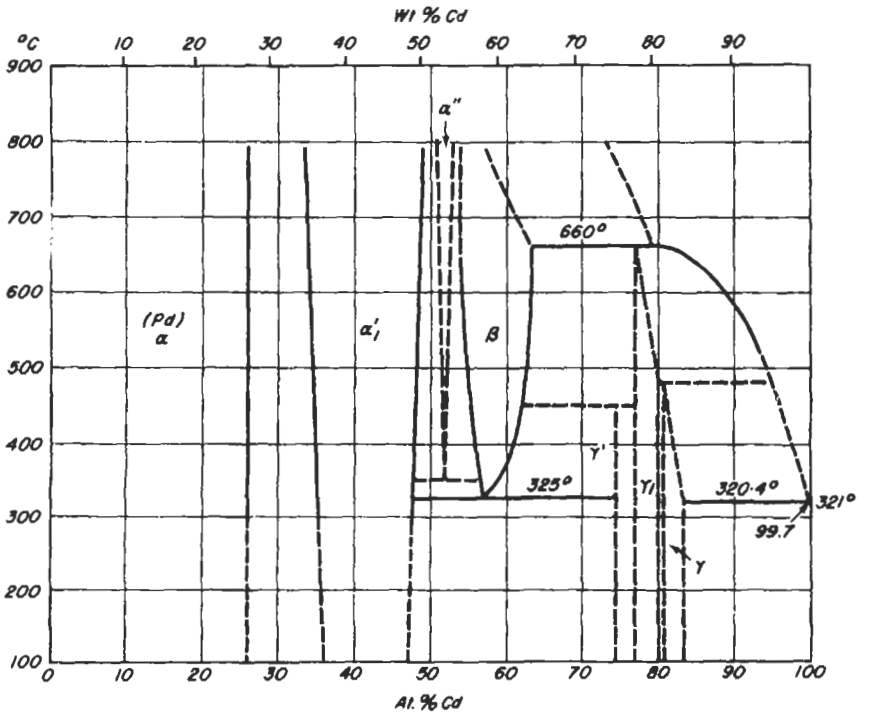
Cd–Np



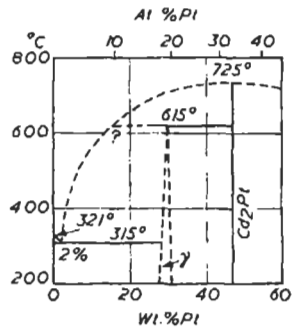
Cd–Pb



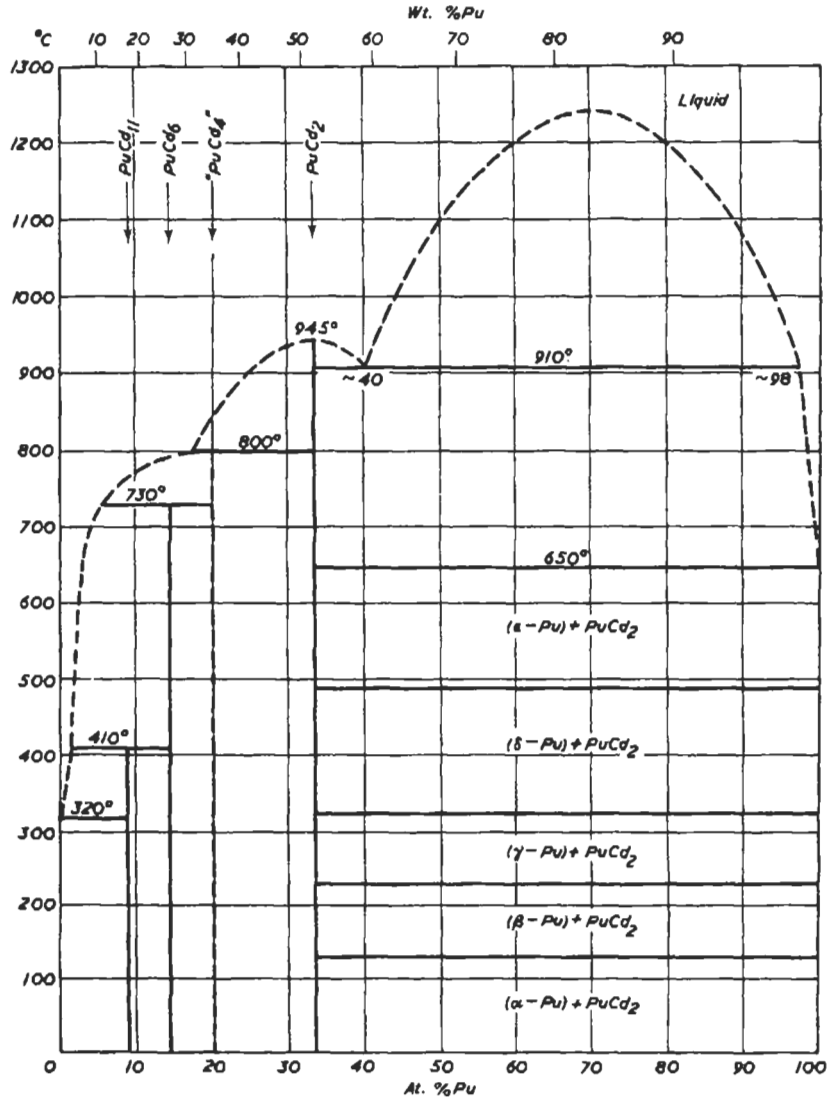
Cd–Pd



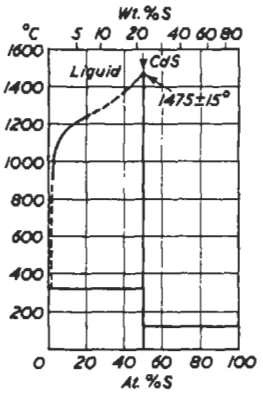
Cd–Pt


At %Pt
°C
10
20
30
40
800
600
400
200
725°
615°
321°
315°
2%
γ
Cd2Pt
0
20
40
60
Wt.%Pt

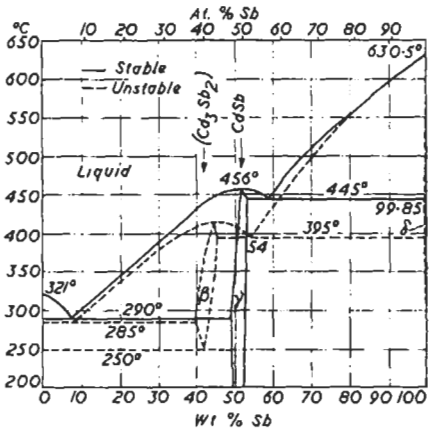
Cd–Pu


Wt. %Pu
°C
10
20
30
40
50
60
70
80
90
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
PuCd11
PuCd6
"PuCd4"
PuCd2
Liquid
945°
~40
910°
~98
800°
730°
650°
410°
320°
(ε − Pu) + PuCd2
(δ − Pu) + PuCd2
(γ − Pu) + PuCd2
(β − Pu) + PuCd2
(α − Pu) + PuCd2
0
10
20
30
40
50
60
70
80
90
100
At. %Pu

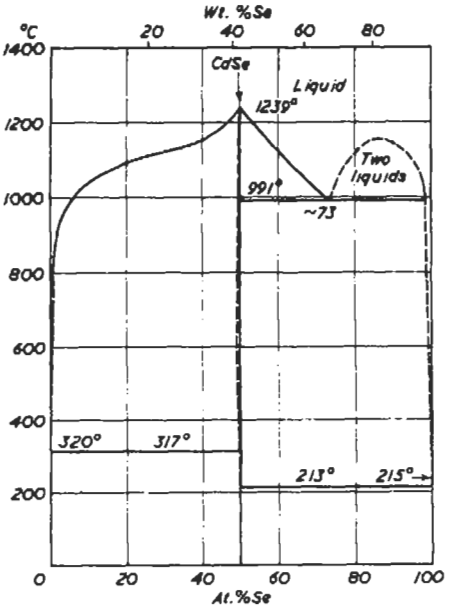
Cd–S



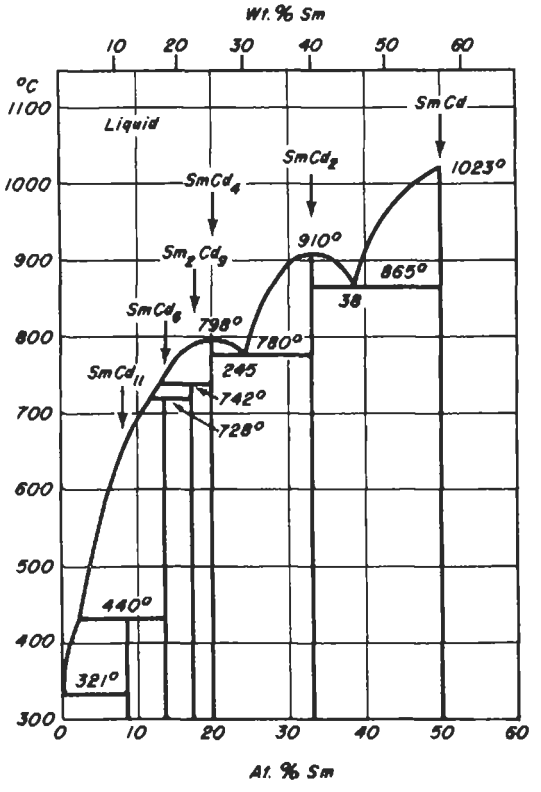
Cd–Sb



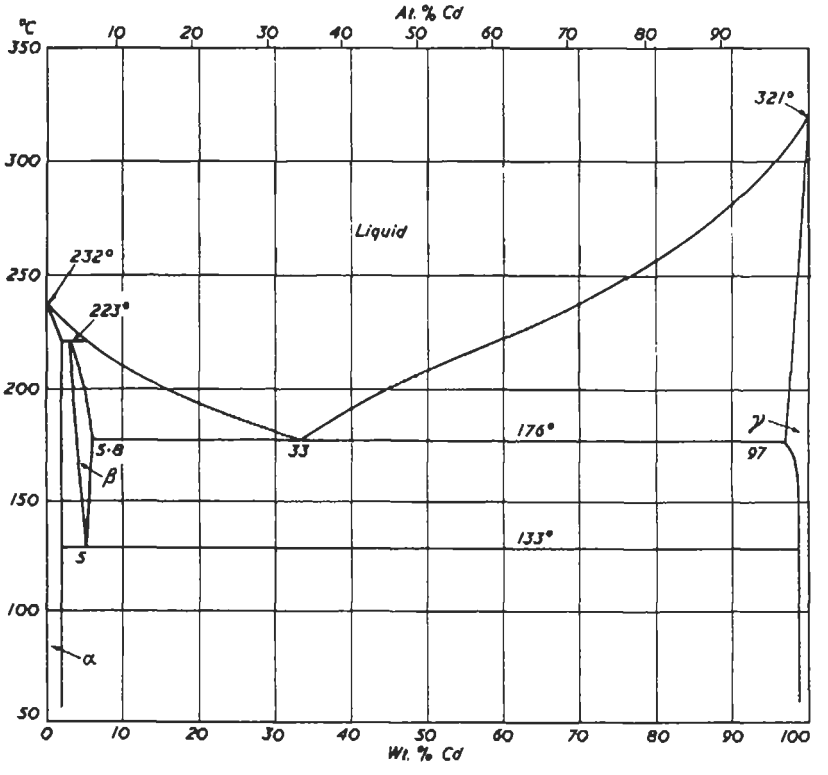
Cd–Se



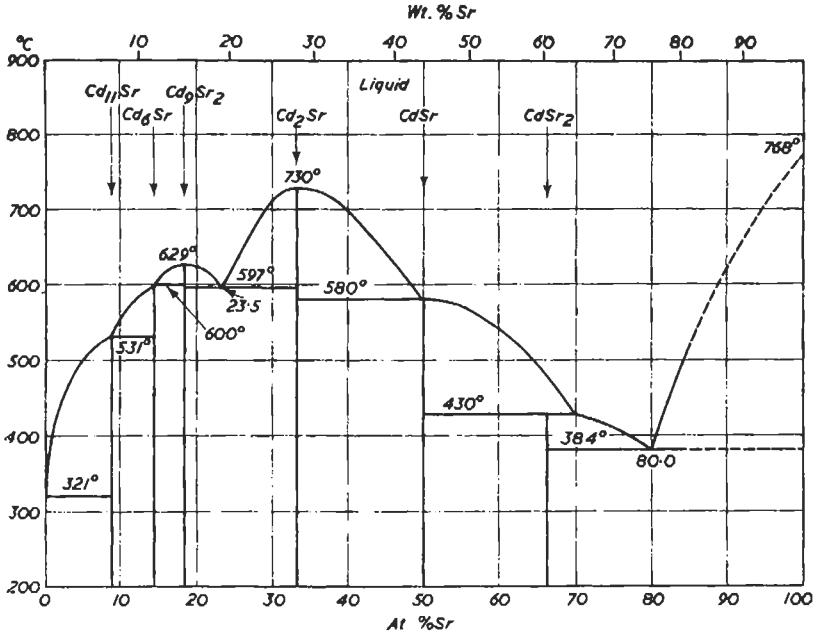
Cd–Sm


Wt. % Sm
10
20
30
40
50
60
°C
1100
1000
900
800
700
600
500
400
300
Liquid
SmCd
1023°
SmCd2
910°
SmCd4
Sm2Cd3
865°
38
SmCd6
798°
780°
SmCd11
245
742°
728°
440°
321°
0
10
20
30
40
50
60
At. % Sm

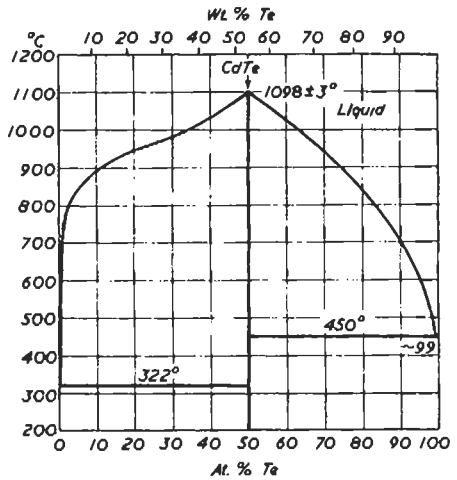
Cd–Sn


At. % Cd
°C
10
20
30
40
50
60
70
80
90
350
300
250
200
150
100
50
321°
Liquid
232°
223°
176°
γ
97
5·8
β
33
133°
5
α
0
10
20
30
40
50
60
70
80
90
100
Wt. % Cd

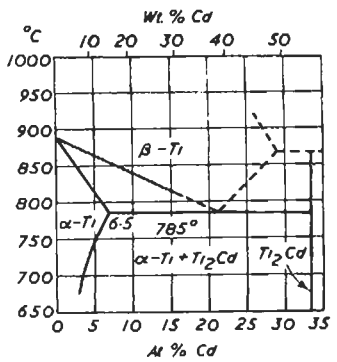
Cd–Sr



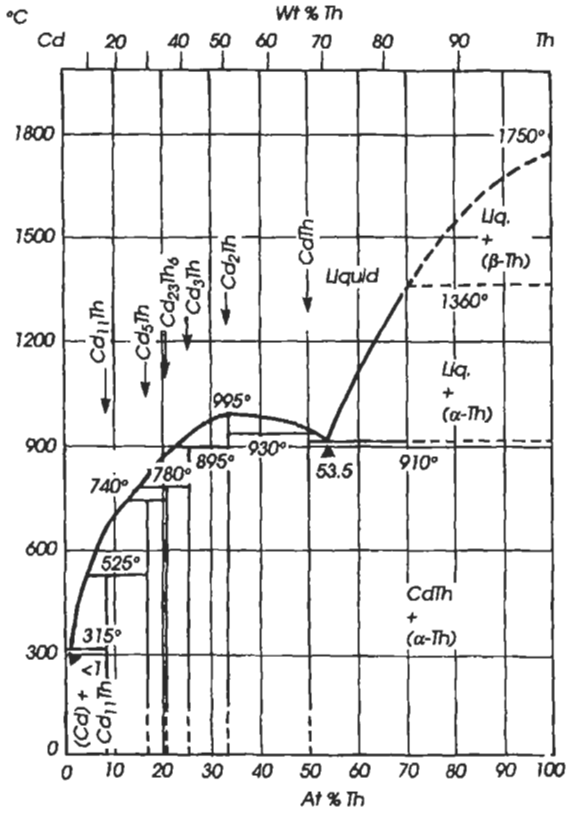
Cd–Te



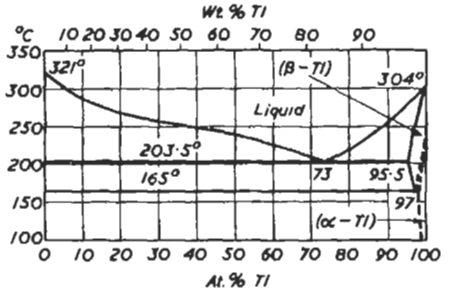
Cd–Ti



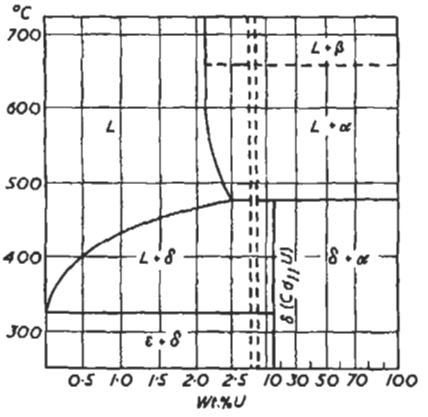
Cd–Th



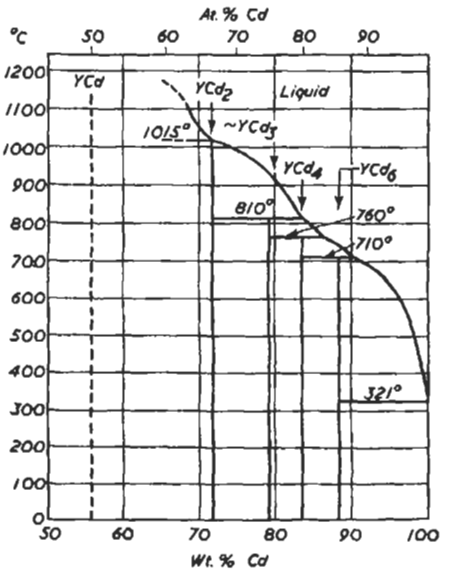
Cd–Tl



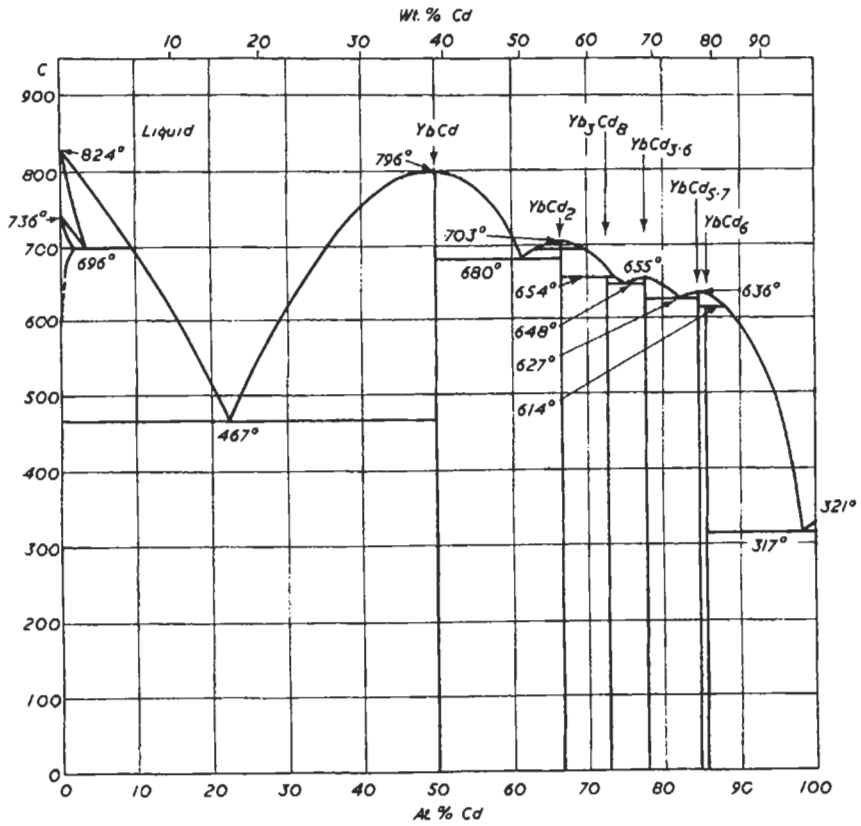
Cd–U



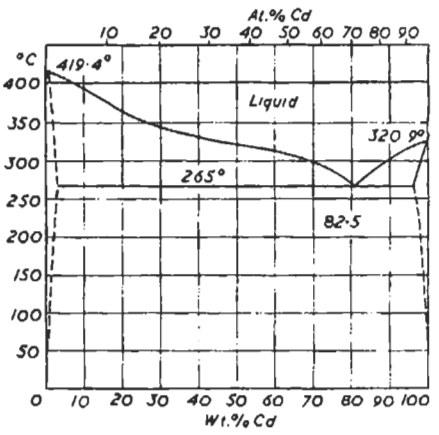
Cd–Y



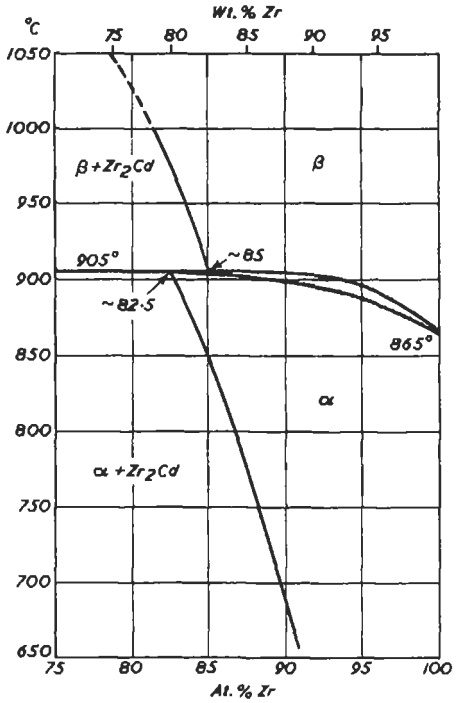
Cd–Yb


Wt. % Cd
10 20 30 40 50 60 70 80 90
C
900
800
700
600
500
400
300
200
100
0
Liquid
824°
736°
696°
YbCd
796°
703°
680°
YbCd2
Yb3Cd8
YbCd3·6
YbCd5·7
YbCd6
654°
655°
648°
627°
614°
636°
467°
321°
317°
0 10 20 30 40 50 60 70 80 90 100
At % Cd

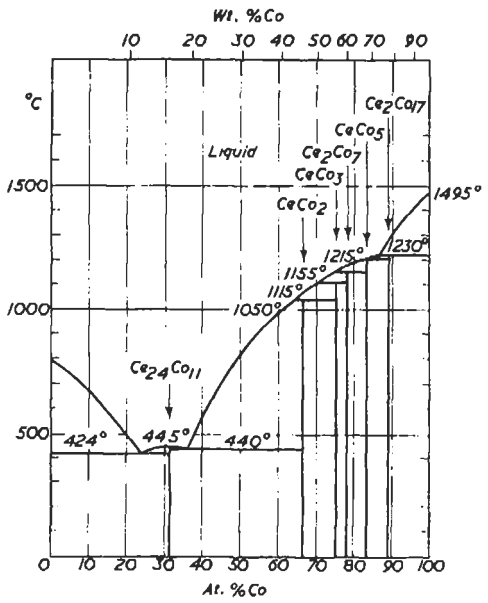
Cd–Zn


At.% Cd
10 20 30 40 50 60 70 80 90
°C
400
350
300
250
200
150
100
50
0
419·4°
Liquid
320·9°
265°
82·5
0 10 20 30 40 50 60 70 80 90 100
Wt.% Cd

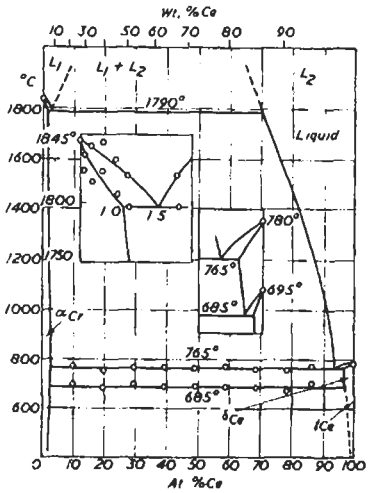
Cd–Zr


Wt. % Zr
°C
75 80 85 90 95
1050
1000
950
900
850
800
750
700
650
β+Zr2Cd
β
905°
~85
~82·5
865°
α
α+Zr2Cd
75 80 85 90 95 100
At. % Zr

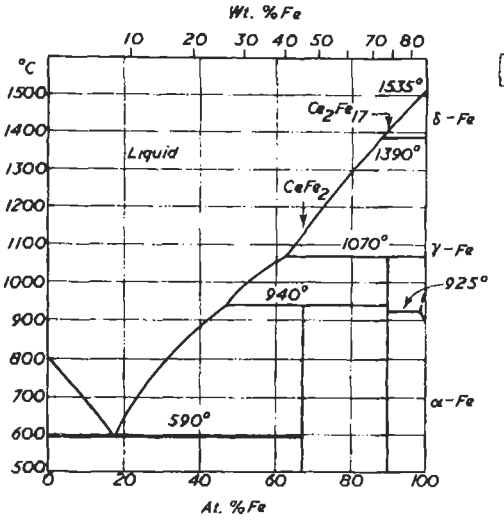
Ce–Co


Wt. %Co
10 20 30 40 50 60 70 90
°C
Ce2Co17
CeCo5
Liquid
Ce2Co7
CeCo3
CeCo2
1495°
1230°
1215°
1155°
1115°
1050°
1500
1000
500
Ce24Co11
424°
445°
440°
0 10 20 30 40 50 60 70 80 90 100
At. %Co

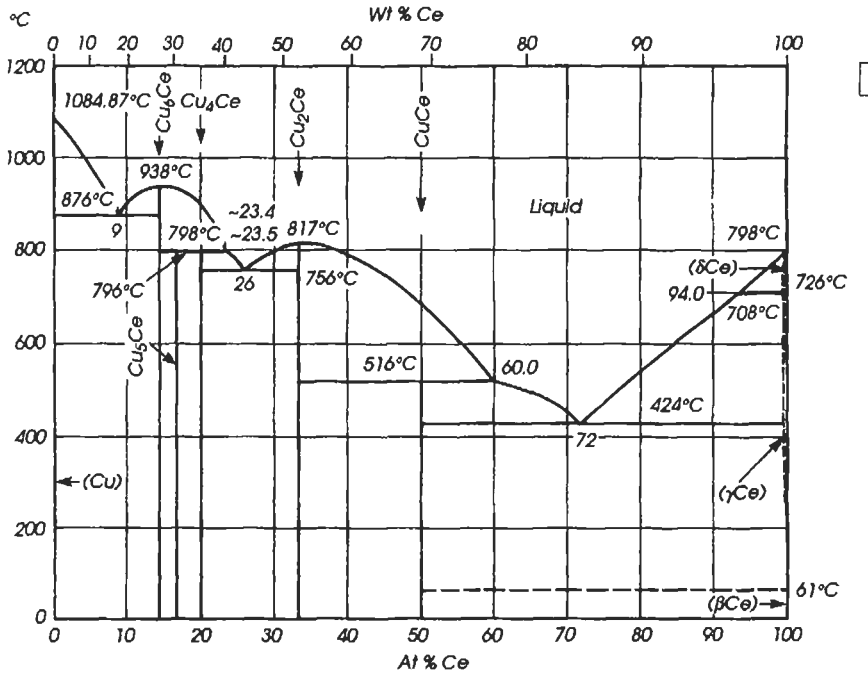
Ce–Cr



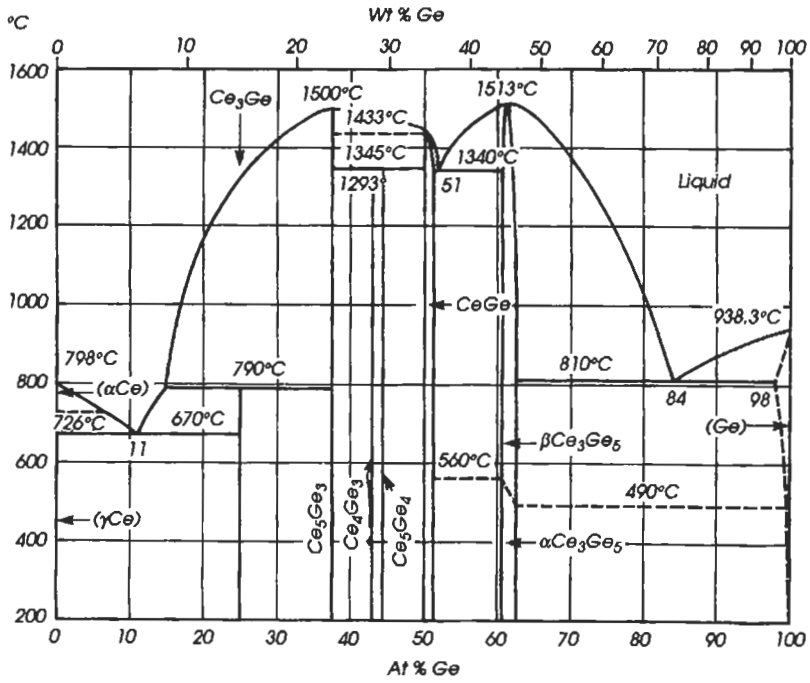
Ce–Fe



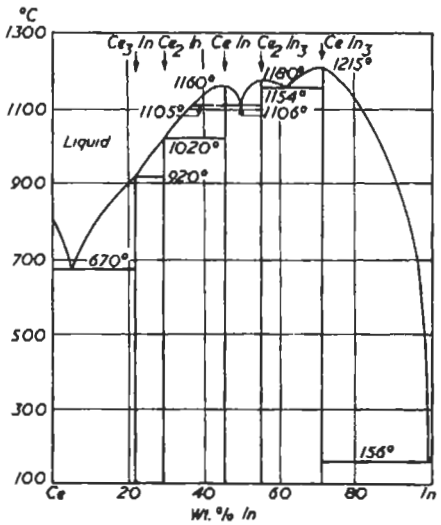
Ce–Cu



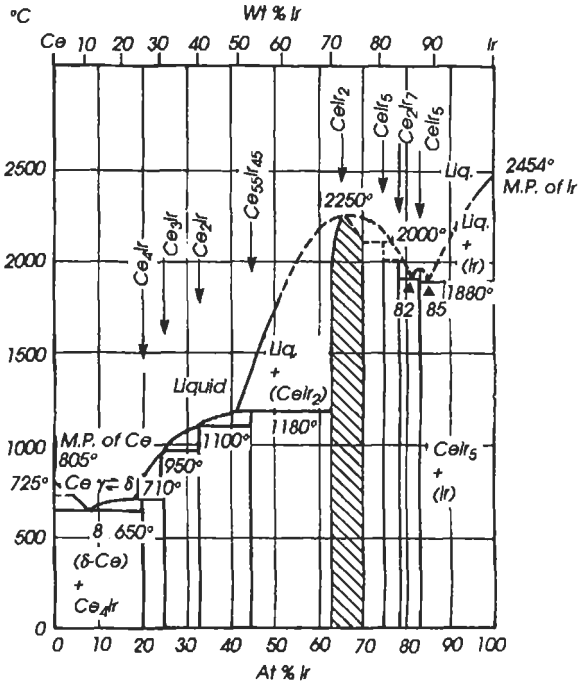
Ce–Ge


°C
Wt % Ge
0 10 20 30 40 50 60 70 80 90 100
1600
1400
1200
1000
800
600
400
200
Ce3Ge
1500°C
1433°C
1345°C
1293°
1513°C
1340°C
51
Liquid
CeGe
938.3°C
798°C
(αCe)
790°C
810°C
84
98
(Ge)
726°C
670°C
11
βCe3Ge5
560°C
490°C
(γCe)
Ce5Ge3
Ce4Ge3
Ce5Ge4
αCe3Ge5
0 10 20 30 40 50 60 70 80 90 100
At % Ge

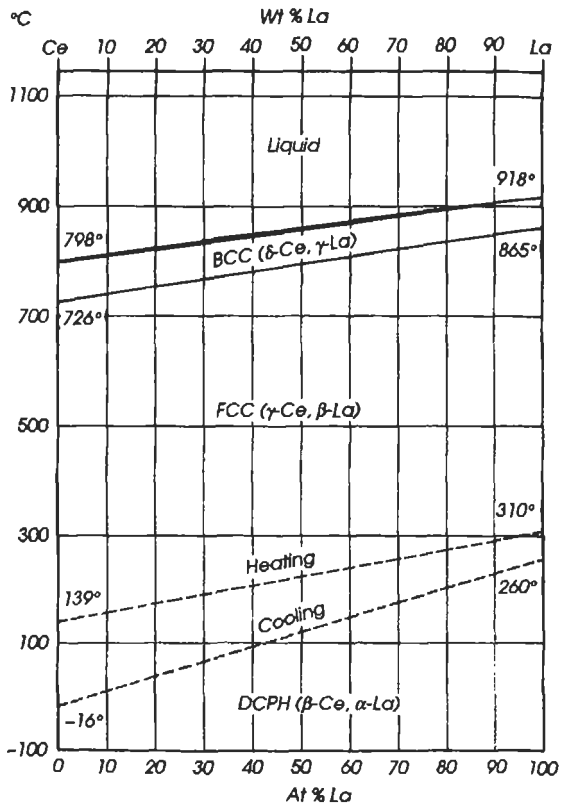
Ce–In


°C
1300
1100
900
700
500
300
100
Ce3In Ce2In Ce In Ce2In3 CeIn3
1160°
1180°
1215°
1105°
1154°
1106°
Liquid
1020°
920°
670°
156°
Ce
20 40 60 80
In
Wt. % In

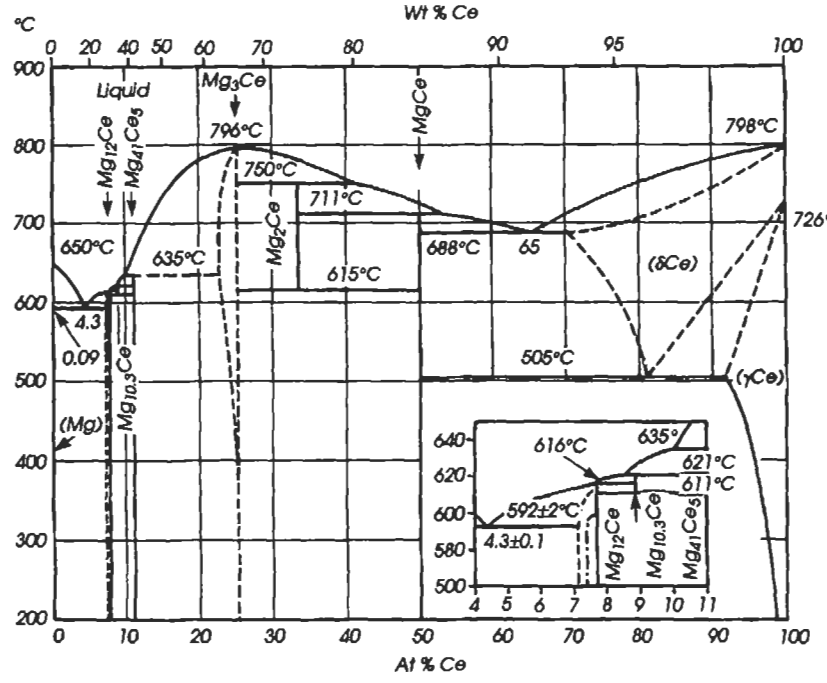
Ce–Ir


°C
Wt % Ir
Ce 10 20 30 40 50 60 70 80 90 Ir
2500
2000
1500
1000
725°
500
0
Ce_4Ir
Ce_3Ir
Ce_2Ir
$Ce_{55}Ir_{45}$
$CeIr_2$
$CeIr_5$
Ce_2Ir_7
$CeIr_5$
Liq.
2454°
M.P. of Ir
2250°
2000°
Liq.
+
(Ir)
1880°
82
85
Liquid
Liq.
+
($CeIr_2$)
1180°
M.P. of Ce
805°
1100°
950°
Ce γ ⇌ δ
710°
δ 650°
(δ-Ce)
+
Ce_4Ir
$CeIr_5$
+
(Ir)
0 10 20 30 40 50 60 70 80 90 100
At % Ir

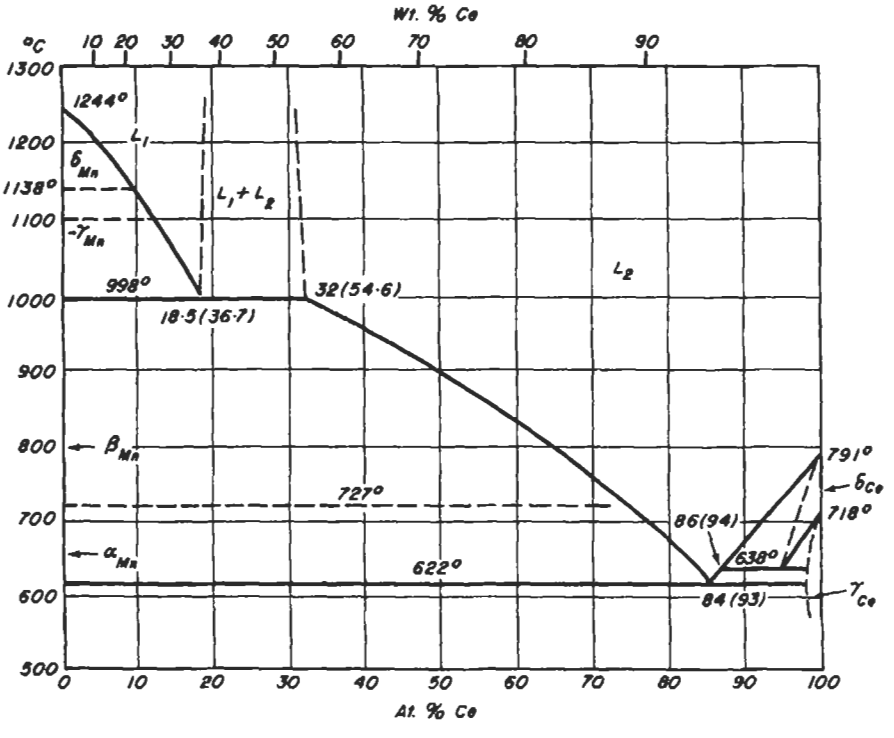
Ce–La


°C
Wt % La
Ce 10 20 30 40 50 60 70 80 90 La
1100
900
798°
700
726°
500
300
139°
100
-16°
-100
Liquid
918°
BCC (δ-Ce, γ-La)
865°
FCC (γ-Ce, β-La)
310°
Heating
260°
Cooling
DCPH (β-Ce, α-La)
0 10 20 30 40 50 60 70 80 90 100
At % La

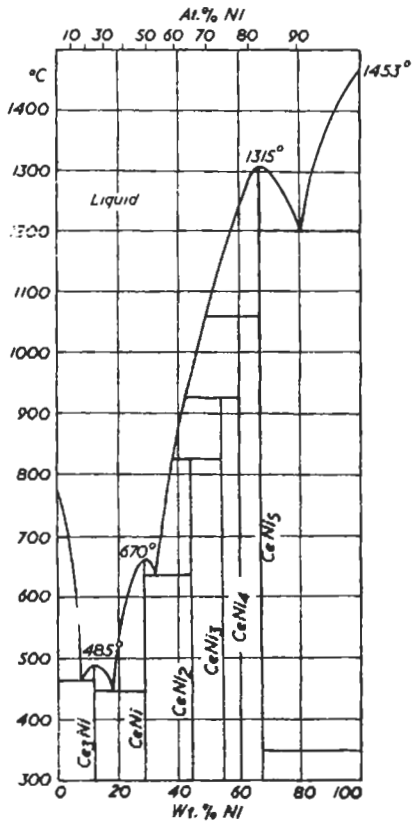
Ce–Mg


Wt % Ce
°C
0 20 40 50 60 70 80 90 95 100
900
800
700
600
500
400
300
200
Liquid
Mg_3Ce
796°C
$Mg_{12}Ce$
$Mg_{41}Ce_5$
750°C
711°C
Mg_2Ce
650°C
635°C
615°C
688°C
65
798°C
726°
(δCe)
505°C
(γCe)
4.3
0.09
(Mg)
$Mg_{10.3}Ce$
MgCe
640
620
600
580
500
616°C
635°
621°C
611°C
592±2°C
4.3±0.1
4 5 6 7 8 9 10 11
0 10 20 30 40 50 60 70 80 90 100
At % Ce

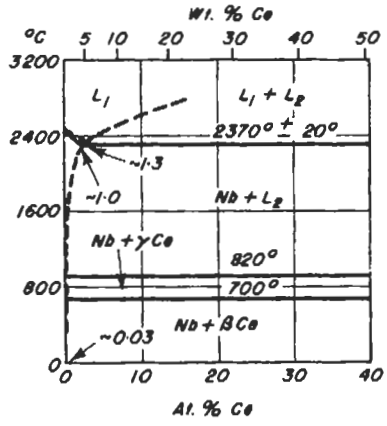
Ce–Mn


Wt. % Ce
°C
10 20 30 40 50 60 70 80 90
1300
1200
1138°
1100
1000
900
800
700
600
500
1244°
L_1
δ_{Mn}
γ_{Mn}
$L_1 + L_2$
998°
18·5(36·7)
32(54·6)
L_2
β_{Mn}
727°
α_{Mn}
622°
86(94)
84(93)
791°
δ_{Ce}
718°
638°
γ_{Ce}
0 10 20 30 40 50 60 70 80 90 100
At. % Ce

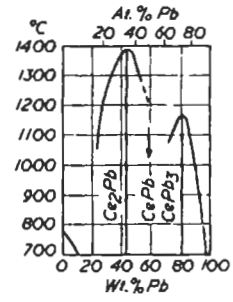
Ce–Ni



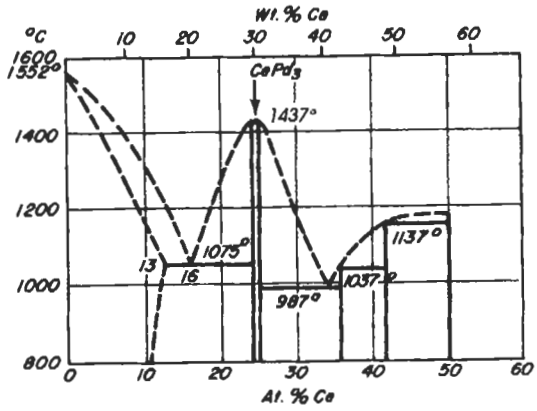
Ce–Nb



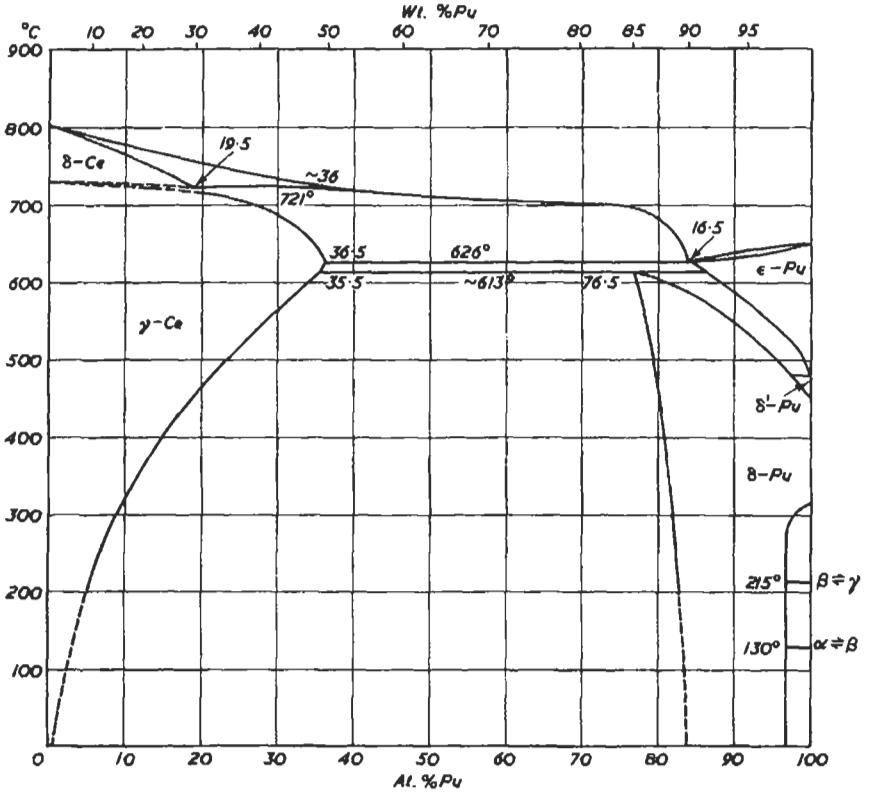
Ce–Pb



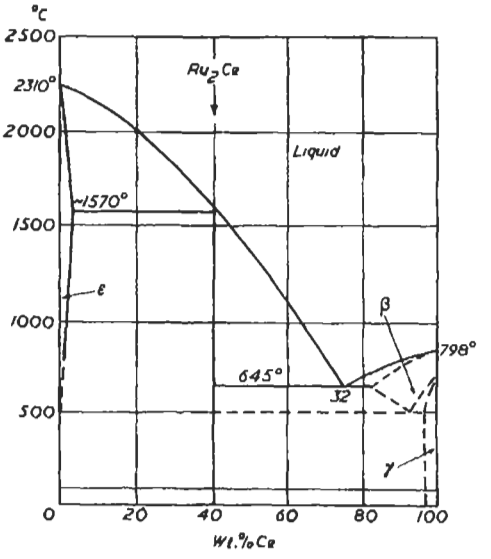
Ce–Pd



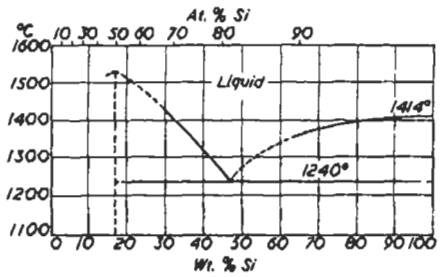
Ce–Pu


Wt. %Pu
°C
10 20 30 40 50 60 70 80 85 90 95
900
800
700
600
500
400
300
200
100
δ–Ce
19·5
~36
721°
36·5
626°
16·5
ε–Pu
35·5
~613°
76·5
γ–Ce
δ'–Pu
δ–Pu
215°
β⇌γ
130°
α⇌β
0 10 20 30 40 50 60 70 80 90 100
At. %Pu

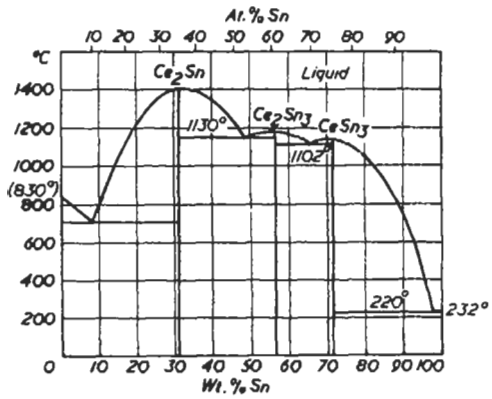
Ce–Ru


°C
2500
2310°
2000
1500
1000
500
Ru₂Ce
Liquid
~1570°
ε
β
798°
645°
32
γ
0 20 40 60 80 100
Wt.%Ce

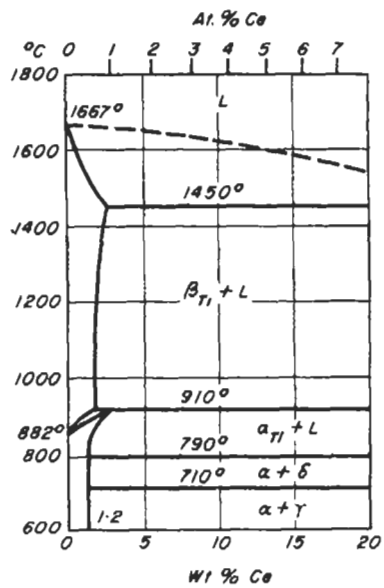
Ce–Si



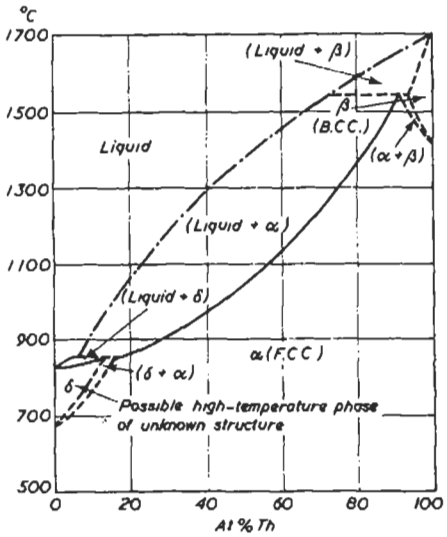
Ce–Sn



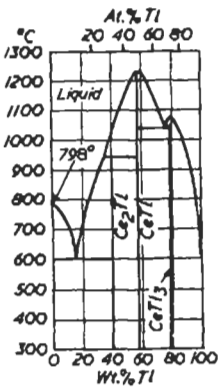
Ce–Ti



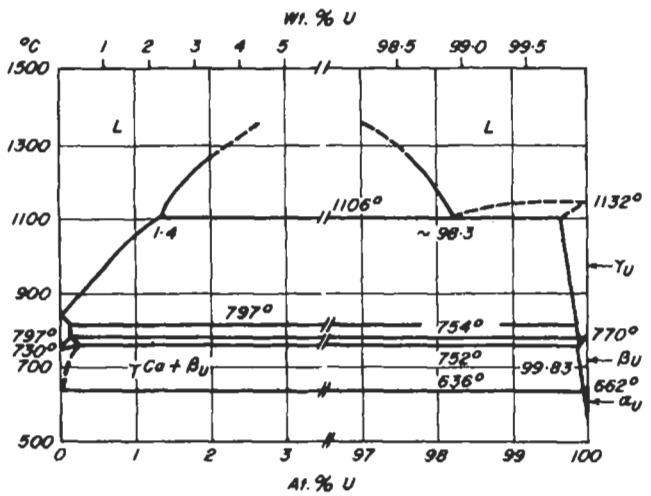
Ce–Th



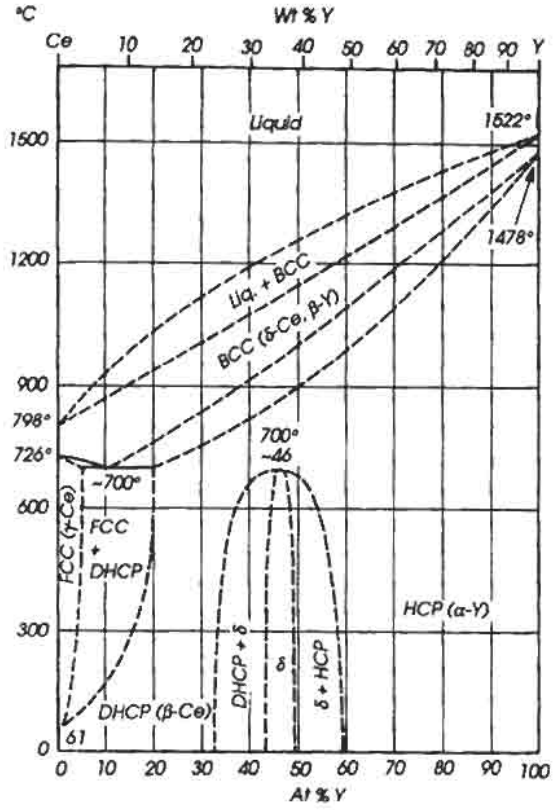
Ce–Tl



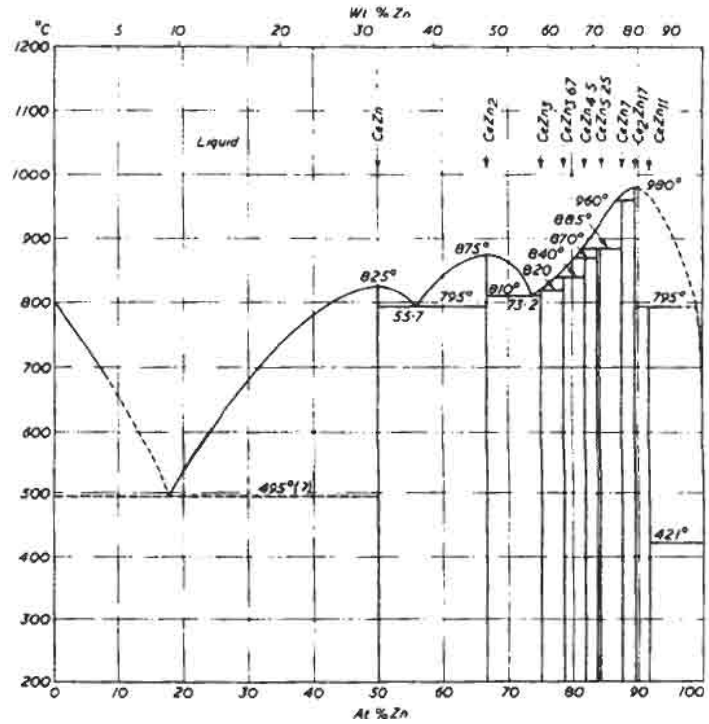
Ce–U



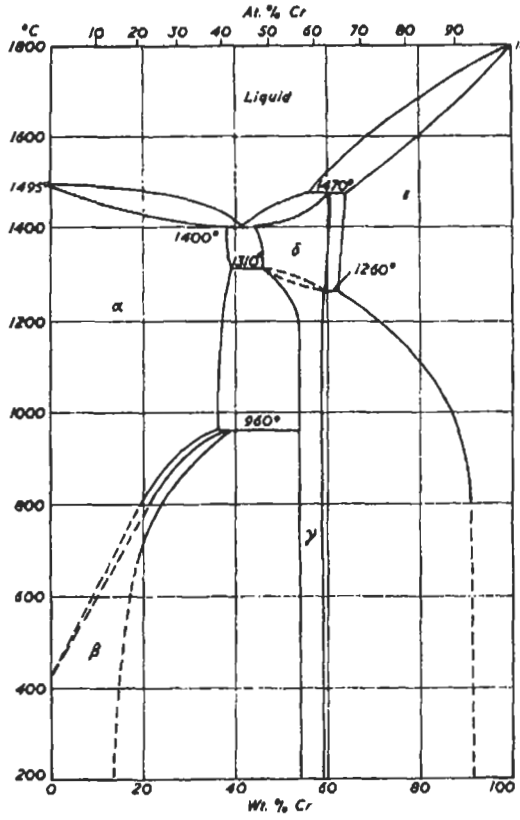
Ce–Y


°C
Wt % Y
Ce
10
20
30
40
50
60
70
80
90
Y
Liquid
1522°
1478°
Liq. + BCC
BCC (δ-Ce, β-Y)
1500
1200
900
798°
726°
700°
~46
~700°
600
FCC (γ-Ce)
FCC
+
DHCP
300
0
DHCP (β-Ce)
61
DHCP + δ
δ
δ + HCP
HCP (α-Y)
0
10
20
30
40
50
60
70
80
90
100
At % Y

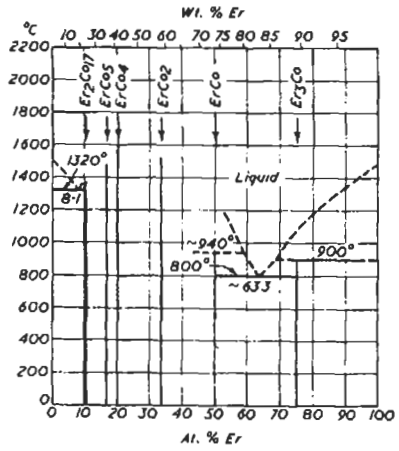
Ce–Zn


Wt % Zn
°C
5
10
20
30
40
50
60
70
80
90
1200
1100
1000
900
800
700
600
500
400
300
200
Liquid
CeZn
CeZn2
CeZn3
CeZn3 67
CeZn4 5
CeZn5 25
CeZn7
Ce2Zn17
CeZn11
990°
960°
885°
870°
840°
820
875°
825°
810°
795°
55·7
73·2
795°
495°(?)
421°
0
10
20
30
40
50
60
70
80
90
100
At % Zn

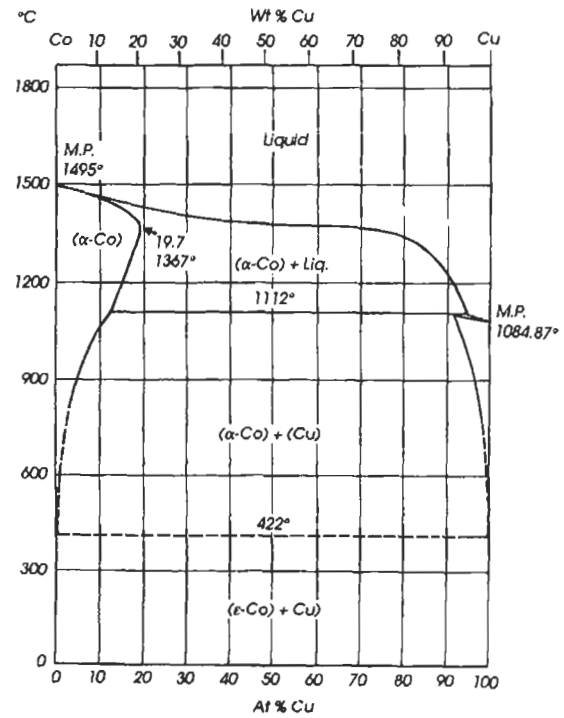
Co–Cr



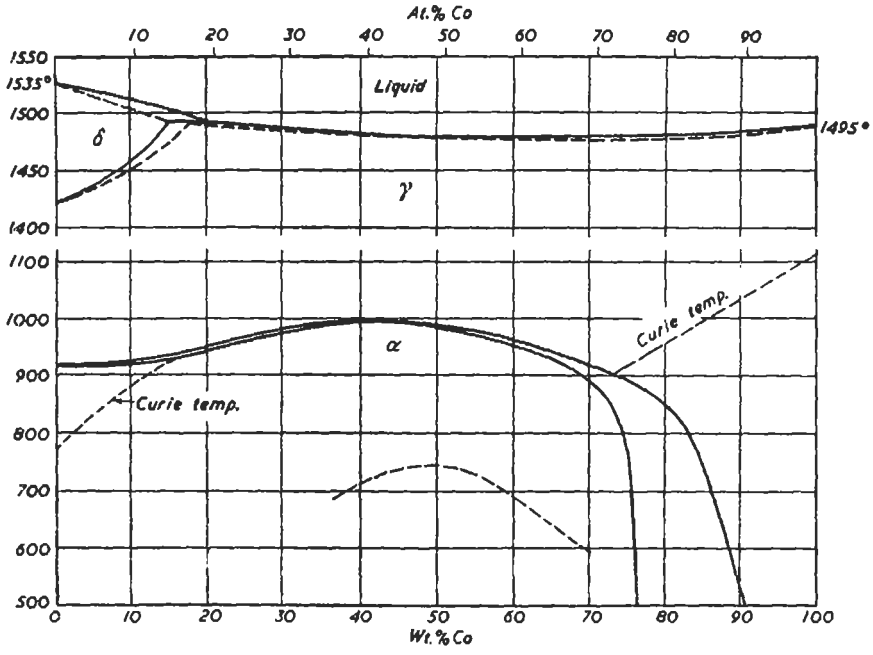
Co–Er



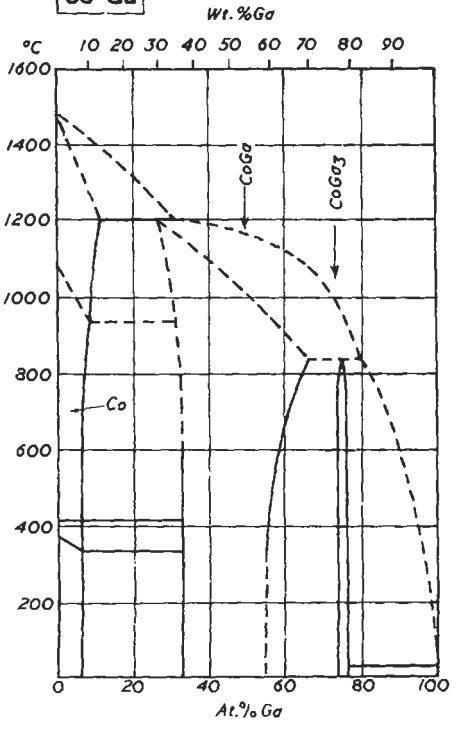
Co–Cu



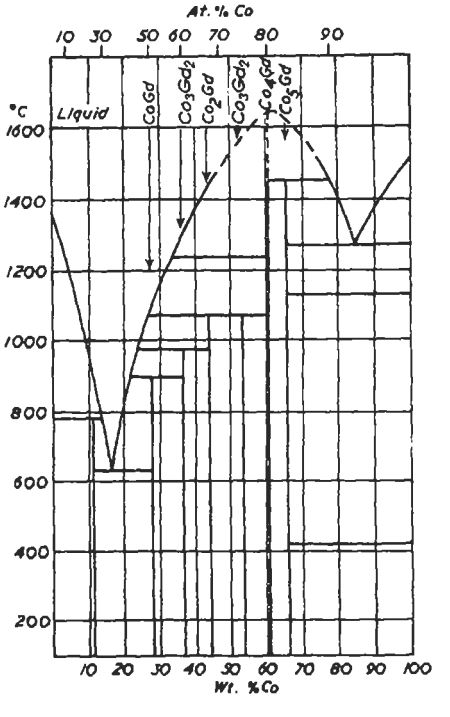
Co–Fe



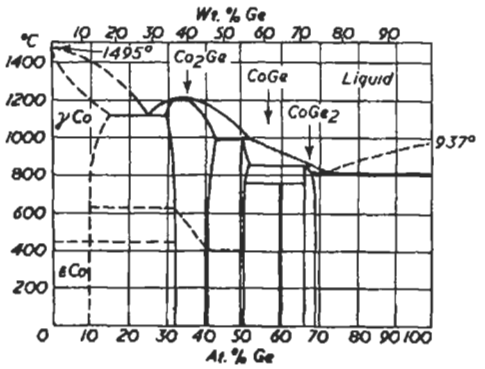
Co–Ga



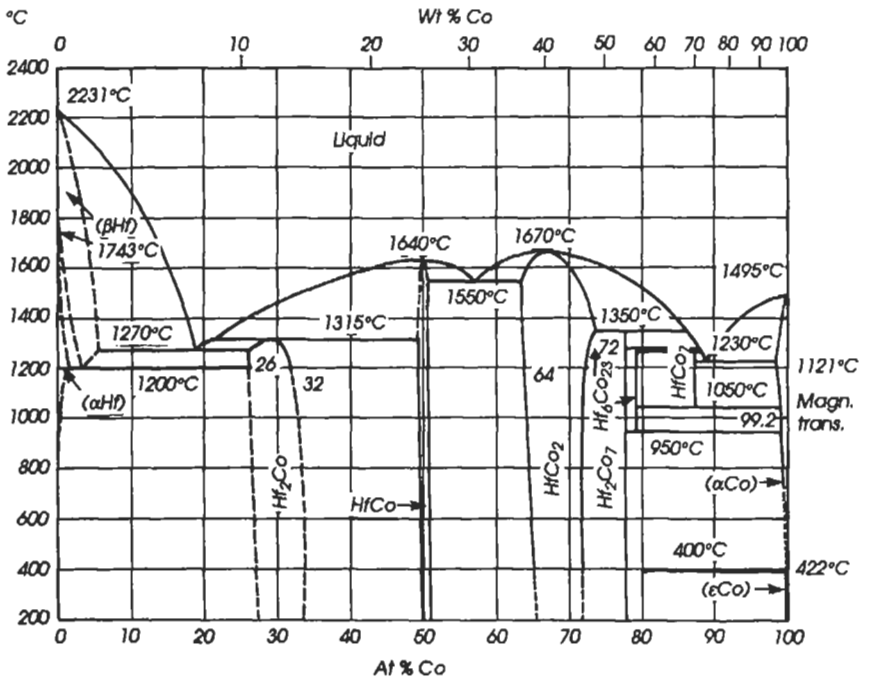
Co–Gd



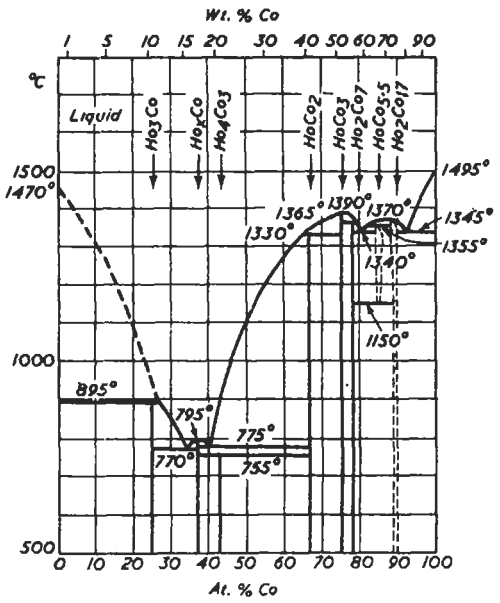
Co–Ge


Wt. % Ge
°C
10 20 30 40 50 60 70 80 90
1400
1200
1000
800
600
400
200
0
1495°
Co2Ge
CoGe
Liquid
CoGe2
γ Co
937°
εCo
10 20 30 40 50 60 70 80 90 100
At. % Ge

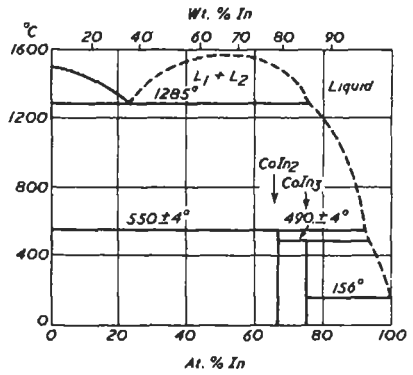
Co–Hf


°C
Wt % Co
0 10 20 30 40 50 60 70 80 90 100
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
2231°C
Liquid
(βHf)
1743°C
1640°C
1670°C
1495°C
1550°C
1350°C
1315°C
1270°C
1230°C
1121°C
72
64
26
32
1200°C
1050°C
Magn. trans.
99.2
950°C
(αHf)
Hf6Co23
HfCo7
Hf2Co
HfCo
HfCo2
Hf2Co7
(αCo)
400°C
422°C
(εCo)
0 10 20 30 40 50 60 70 80 90 100
At % Co

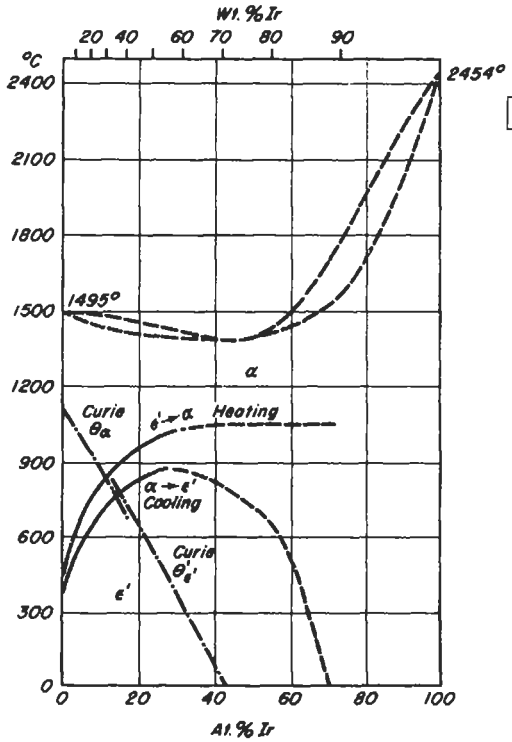
Co–Ho



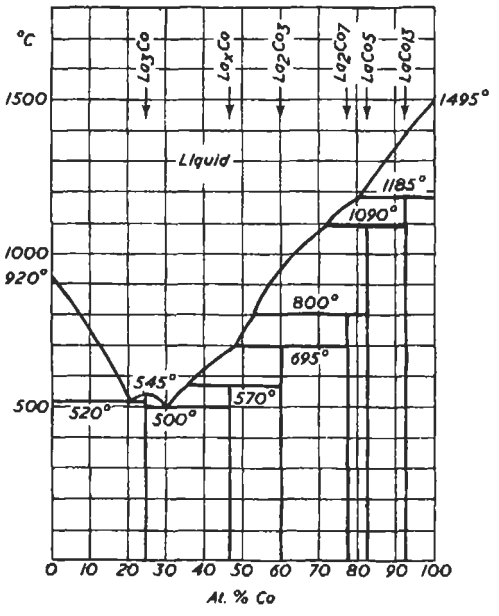
Co–In



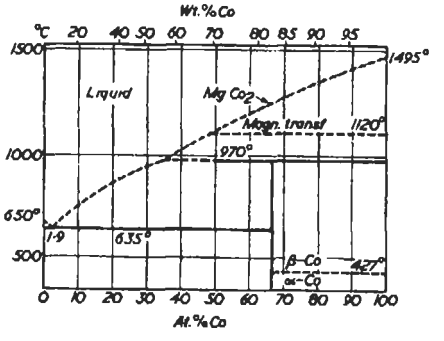
Co–Ir



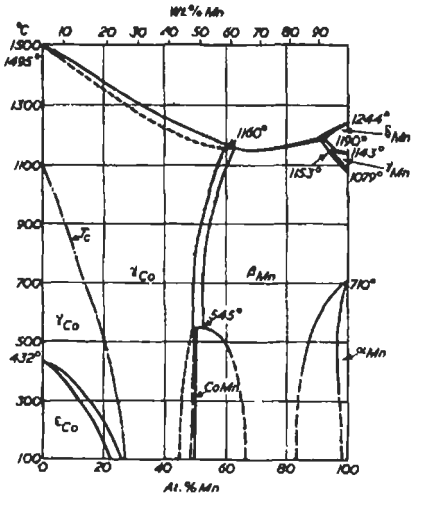
Co–La



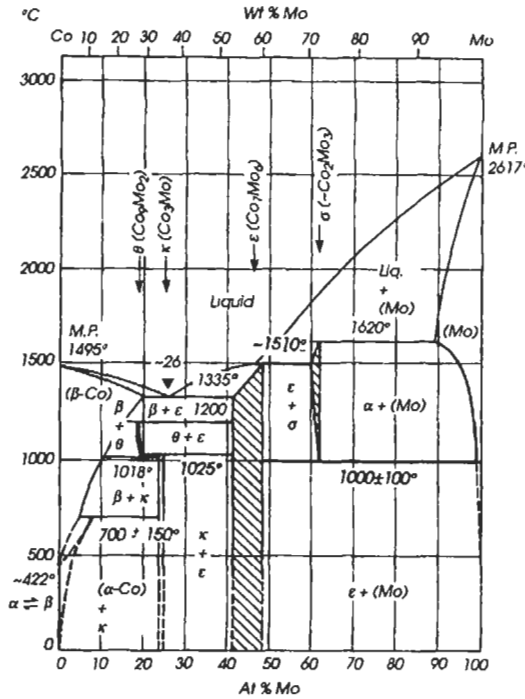
Co–Mg



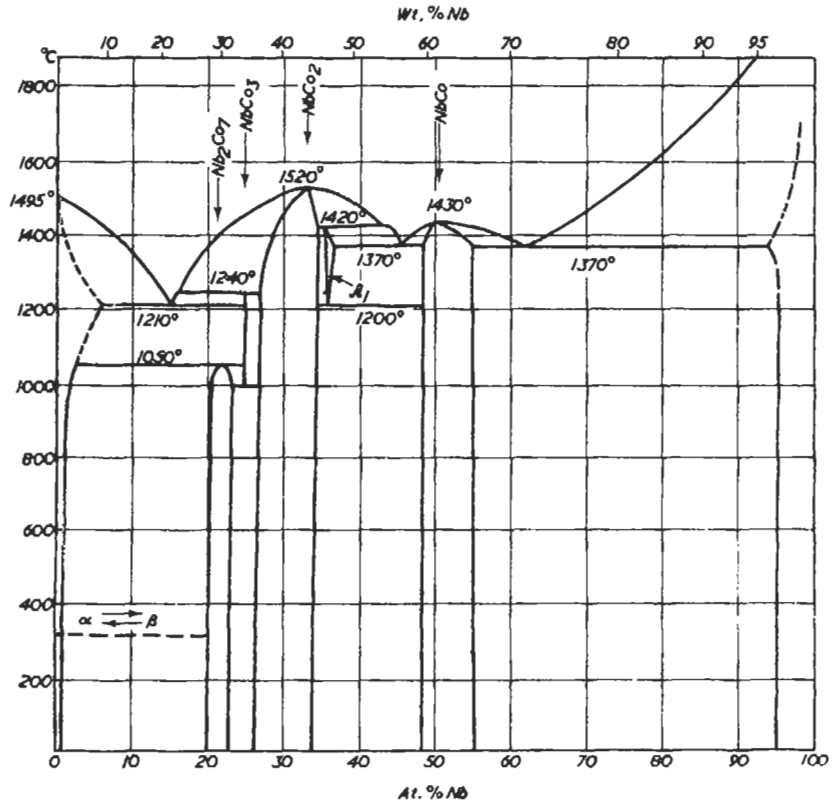
Co–Mn



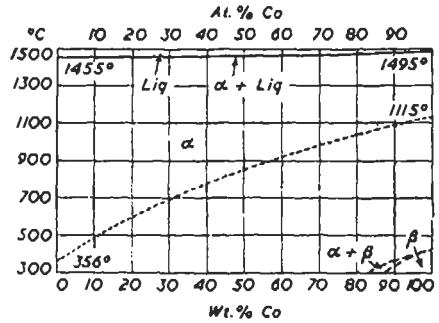
Co–Mo


°C
Wt % Mo
Co 10 20 30 40 50 60 70 80 90 Mo
3000
2500
2000
1500
1000
500
0
θ (Co3Mo2)
κ (Co3Mo)
ε (Co7Mo6)
σ (~Co2Mo3)
M.P.
2617°
Liquid
Liq.
+
(Mo)
1620°
(Mo)
M.P.
1495°
~26
1335°
~1510°
(β-Co)
β
β + ε
1200
θ + ε
ε
+
σ
α + (Mo)
1018°
1025°
1000±100°
β + κ
700 ± 150°
κ
+
ε
~422°
α ⇌ β
(α-Co)
+
κ
ε + (Mo)
0 10 20 30 40 50 60 70 80 90 100
At % Mo

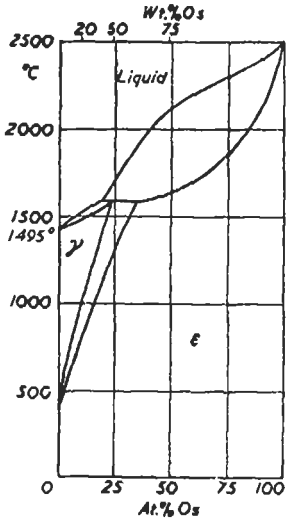
Co–Nb


Wt. % Nb
10 20 30 40 50 60 70 80 90 95
°C
1800
1600
1495°
1400
1200
1000
800
600
400
200
Nb2Co7
NbCo3
NbCo2
NbCo
1520°
1420°
1430°
1370°
1370°
1240°
1210°
1200°
1080°
α ⇌ β
0 10 20 30 40 50 60 70 80 90 100
At. % Nb

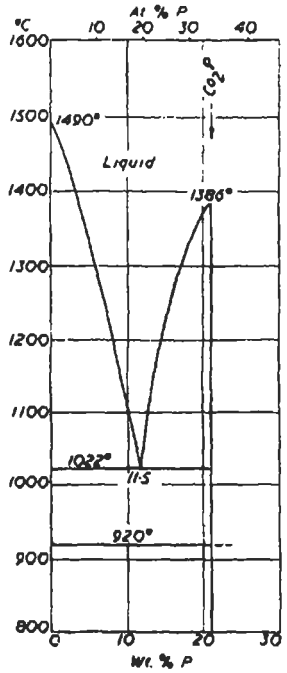
Co–Ni



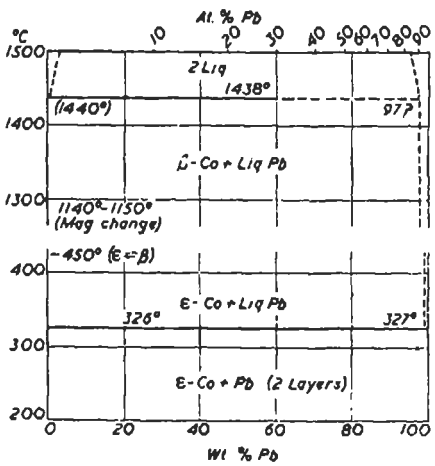
Co–Os



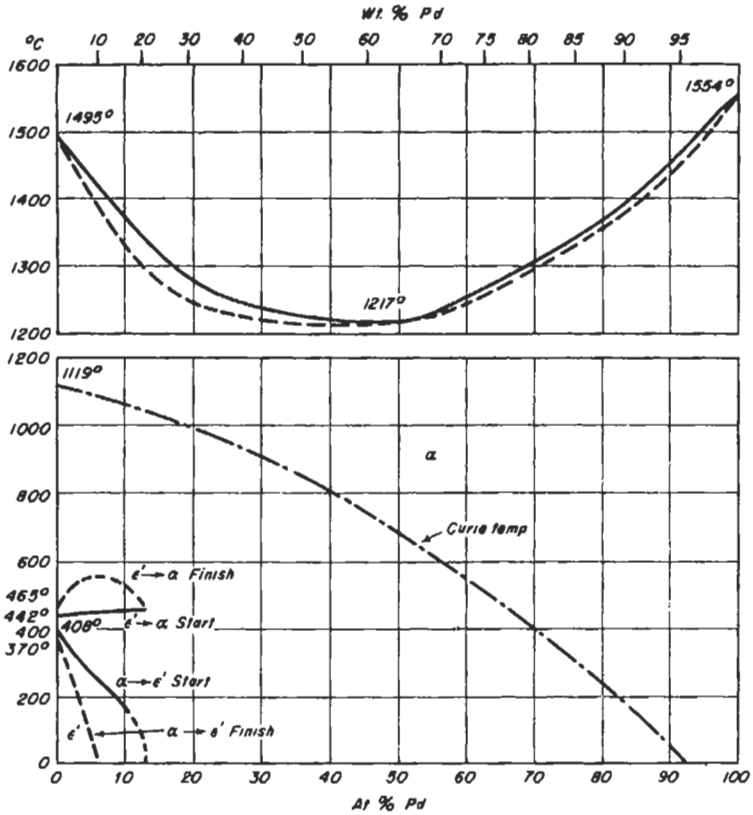
Co–P



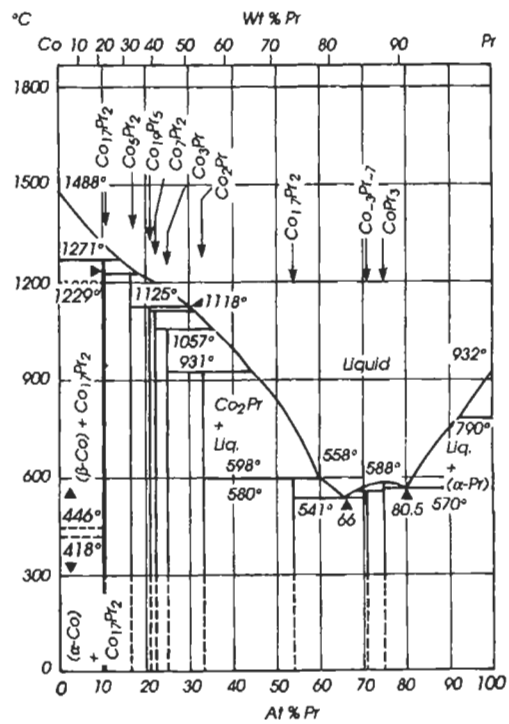
Co–Pb



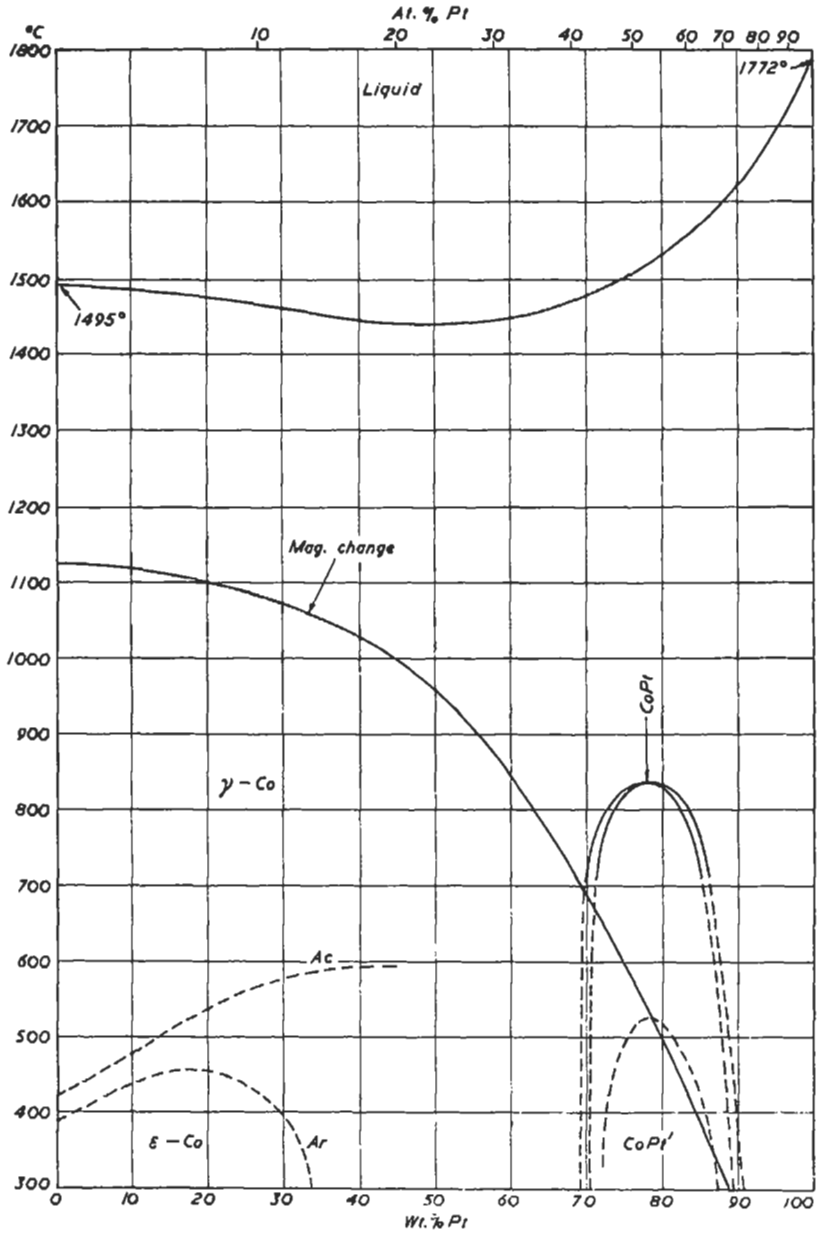
Co–Pd


Wt. % Pd
°C
1495°
1554°
1217°
1119°
α
Curie temp
ε' → α Finish
465°
442°
ε' → α Start
408°
370°
α → ε' Start
ε' → α → ε' Finish
At % Pd

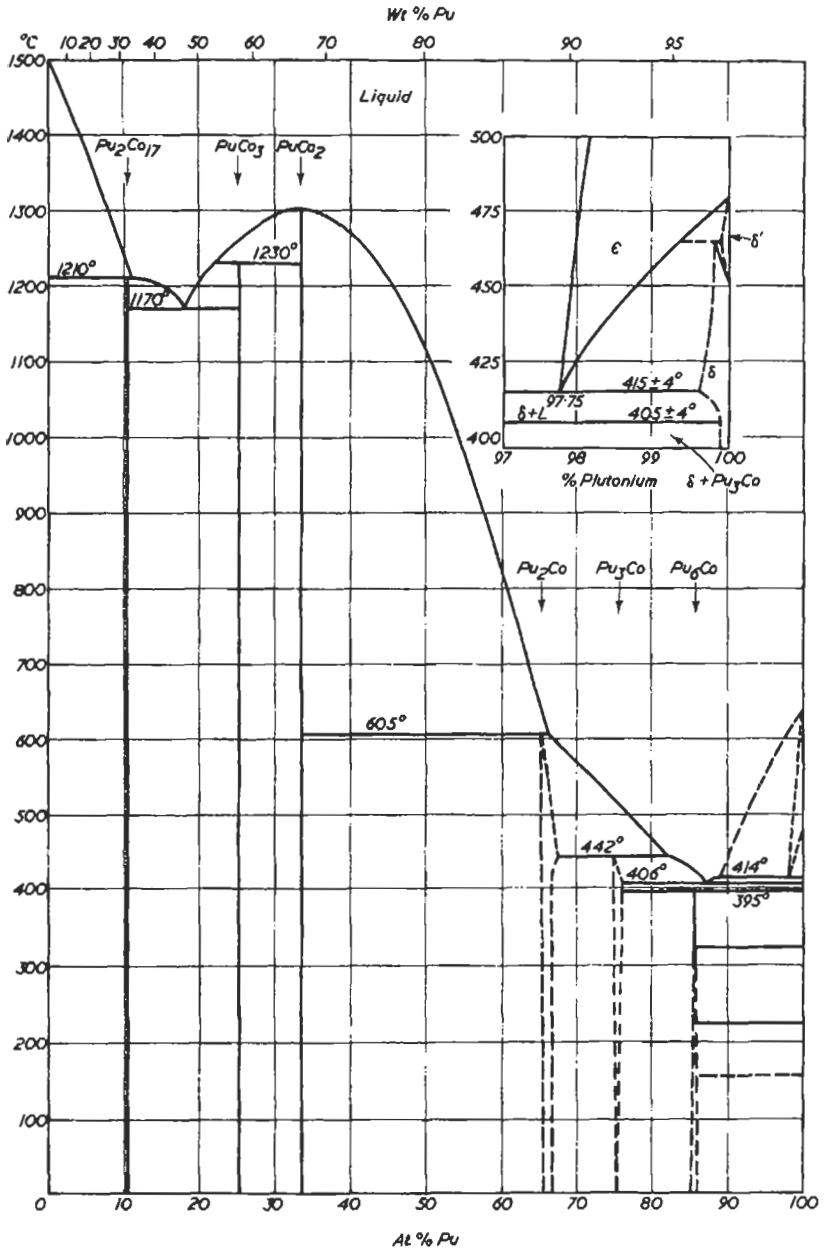
Co–Pr


°C
Wt % Pr
Co
Pr
$Co_{17}Pr_2$
Co_9Pr_2
$Co_{19}Pr_5$
Co_7Pr_2
Co_3Pr
Co_2Pr
$Co_{3-3}Pr_{1-7}$
$CoPr_3$
1488°
1271°
1229°
1125°
1118°
1057°
931°
Liquid
932°
Co_2Pr + Liq.
598°
580°
558°
588°
790°
Liq. + (α-Pr)
541°
66
80.5
570°
446°
418°
(β-Co) + $Co_{17}Pr_2$
(α-Co) + $Co_{17}Pr_2$
At % Pr

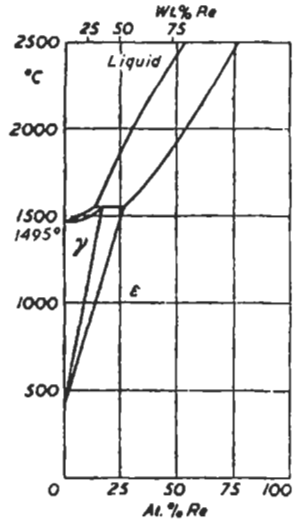
Co–Pt


°C
At. % Pt
10
20
30
40
50
60
70
80
90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
Liquid
1772°
1495°
Mag. change
CoPt
γ – Co
Ac
Ar
ε – Co
CoPt'
0
10
20
30
40
50
60
70
80
90
100
Wt. % Pt

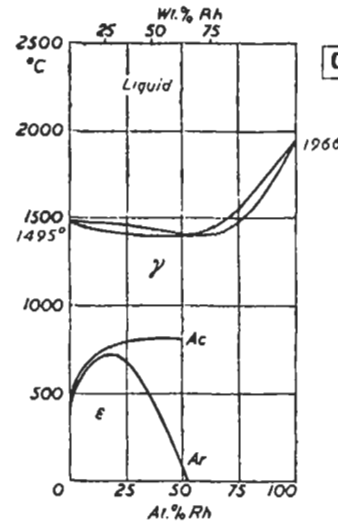
Co–Pu


Wt % Pu
°C
Liquid
Pu_2Co_{17}
$PuCo_3$
$PuCo_2$
1210°
1170°
1230°
605°
Pu_2Co
Pu_3Co
Pu_6Co
442°
406°
414°
395°
ε
δ'
δ
δ+L
415±4°
405±4°
97·75
% Plutonium
δ + Pu_3Co
At % Pu

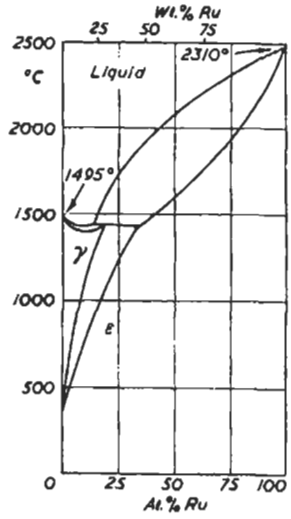
Co–Re



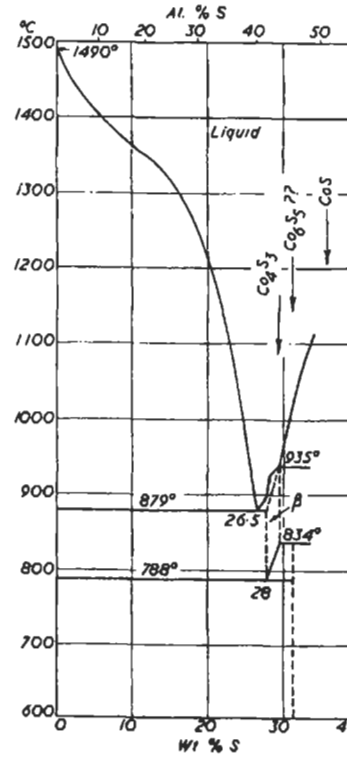
Co–Rh



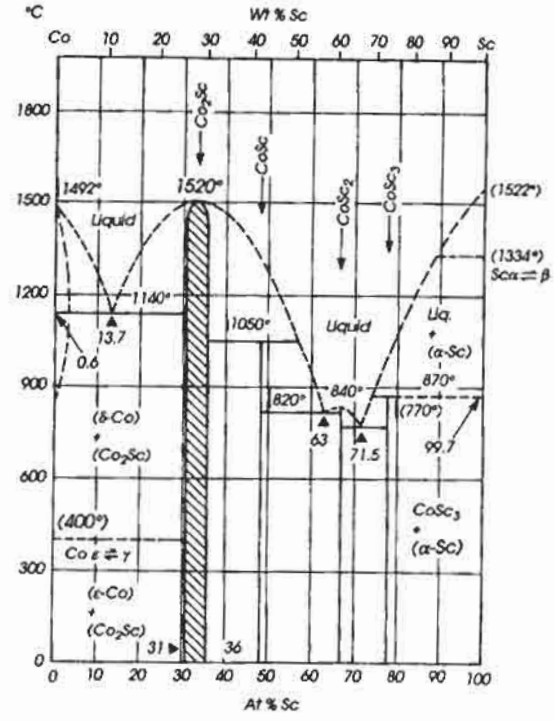
Co–Ru



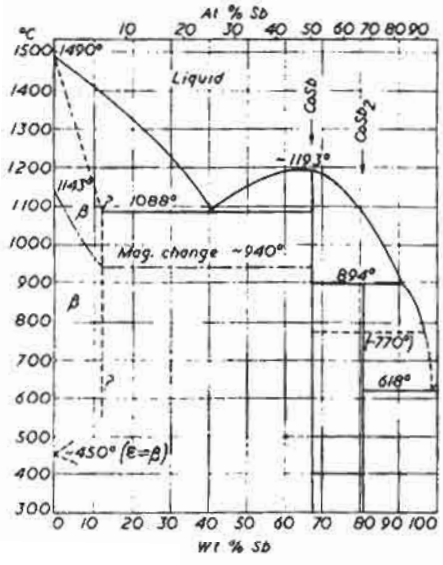
Co–S



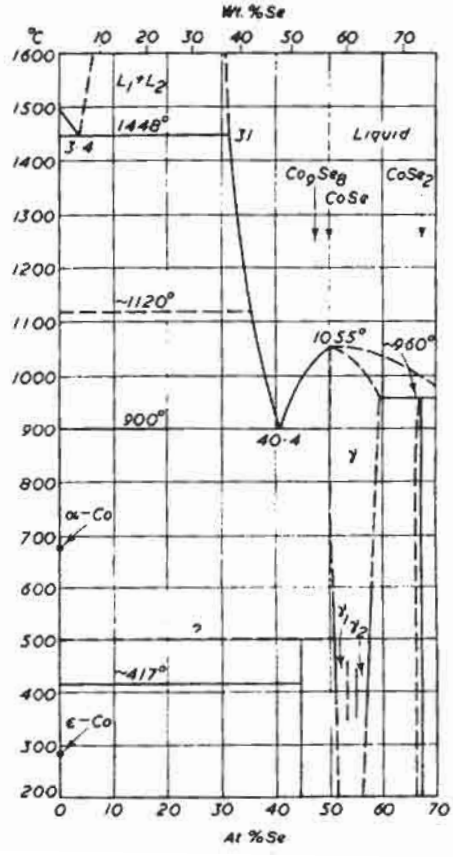
Co–Sc



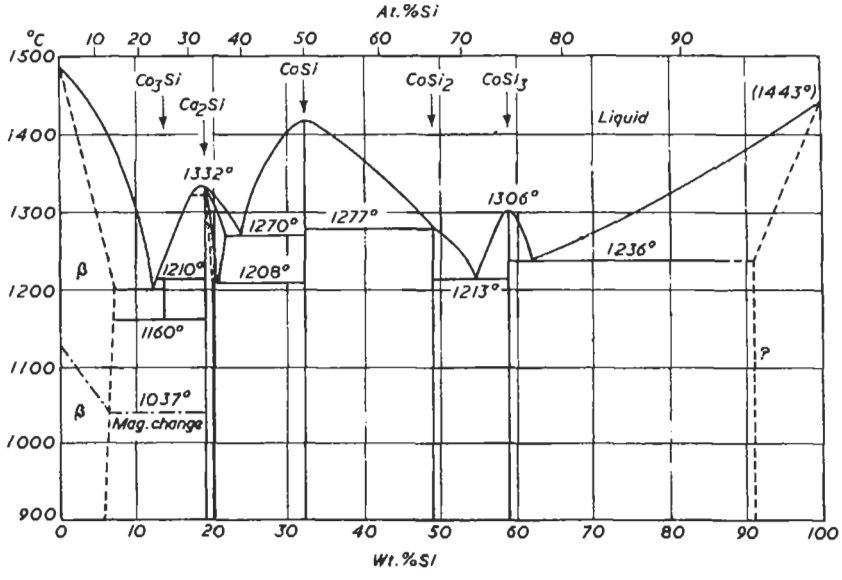
Co–Sb



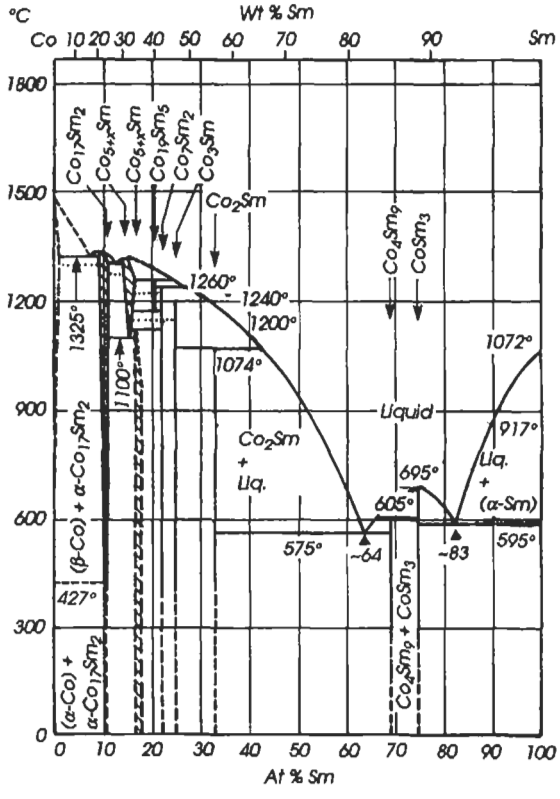
Co–Se

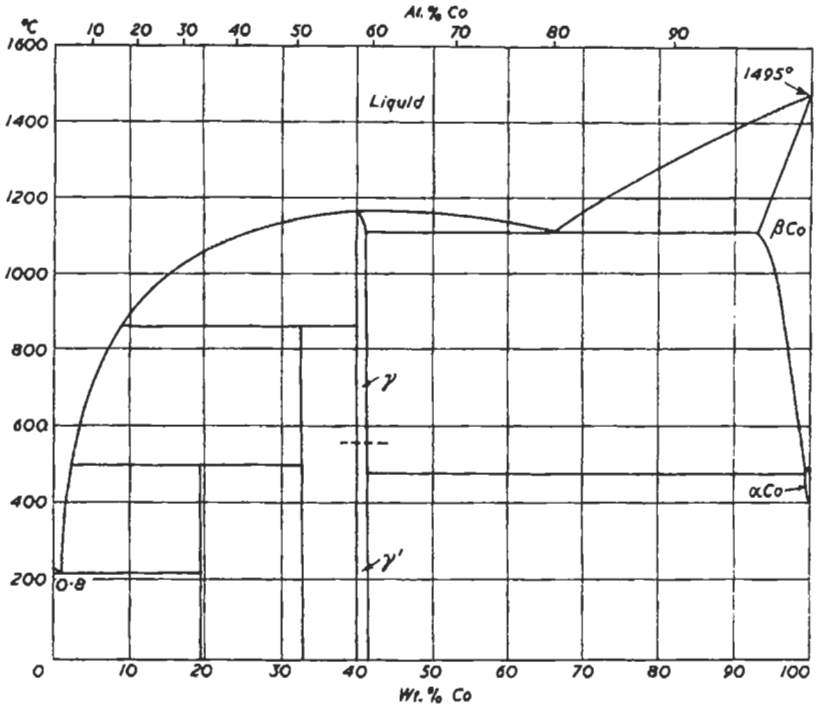


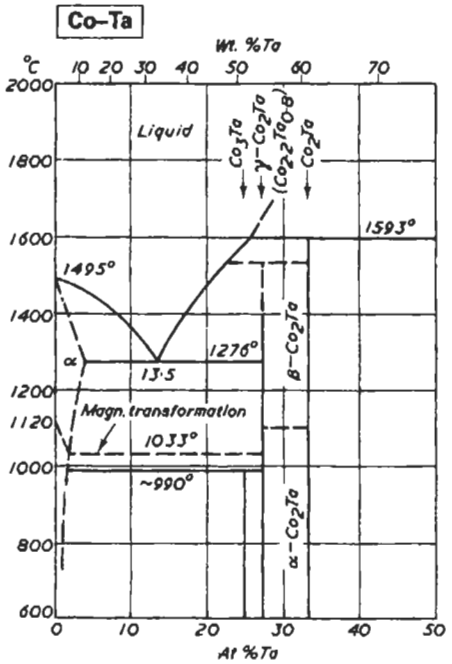
Co–Si

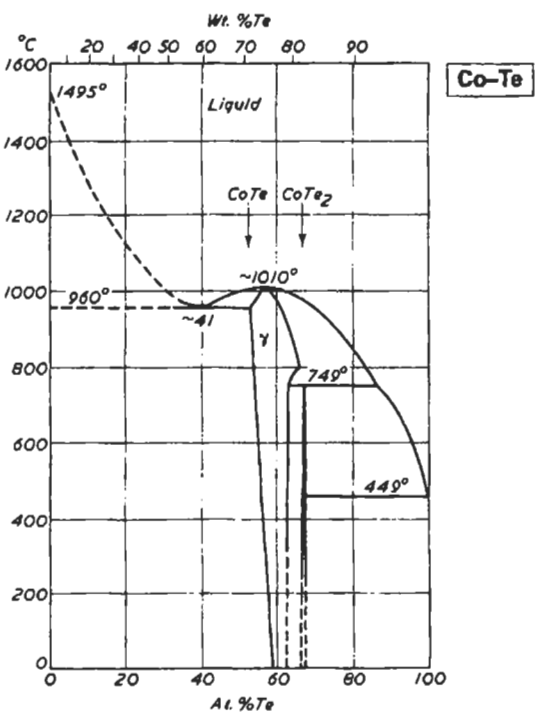

At.%Si
°C
Co3Si
Co2Si
CoSi
CoSi2
CoSi3
Liquid
(1443°)
1332°
1270°
1277°
1306°
1236°
1210°
1208°
1213°
1160°
1037°
Mag. change
β
β
?
Wt.%Si

Co–Sm

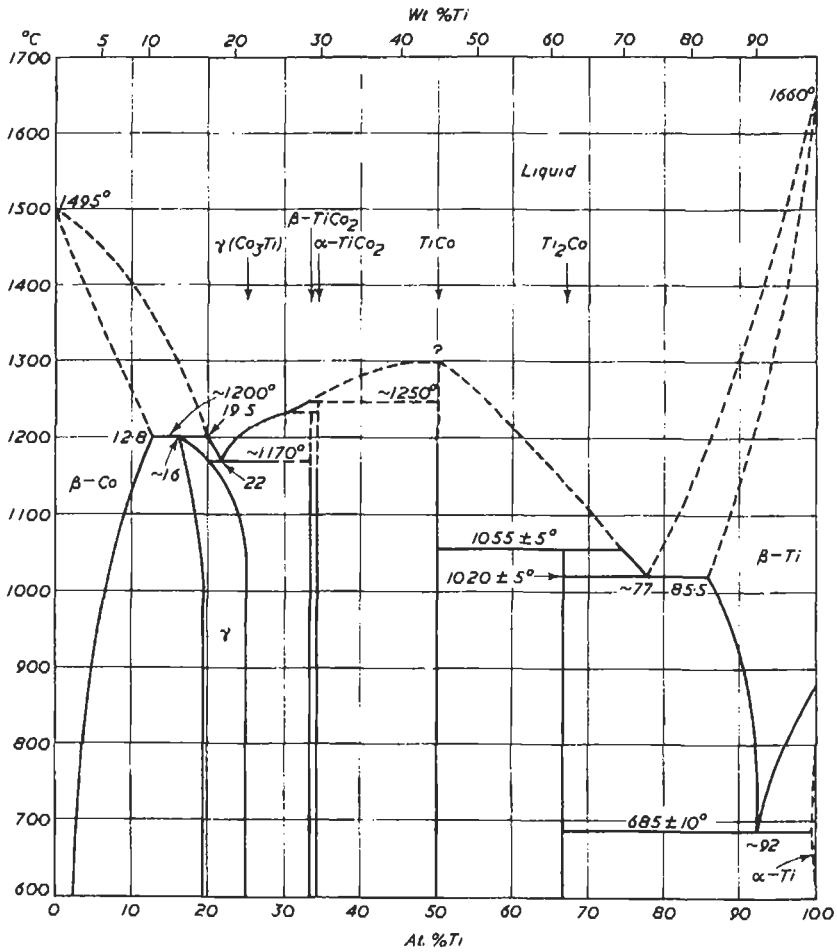

°C
Wt % Sm
Co
Sm
Co17Sm2
Co5+xSm
Co5+xSm
Co19Sm5
Co7Sm2
Co3Sm
Co2Sm
Co4Sm9
CoSm3
1260°
1240°
1200°
1074°
1072°
1325°
1100°
Liquid
917°
Co2Sm
+
Liq.
695°
Liq.
+
(α-Sm)
605°
575°
~64
~83
595°
427°
(β-Co) + α-Co17Sm2
(α-Co) +
α-Co17Sm2
Co4Sm9 + CoSm3
At % Sm


Co–Sn
°C
At. % Co
Liquid
1495°
βCo
αCo
γ
γ'
0·8
Wt. % Co

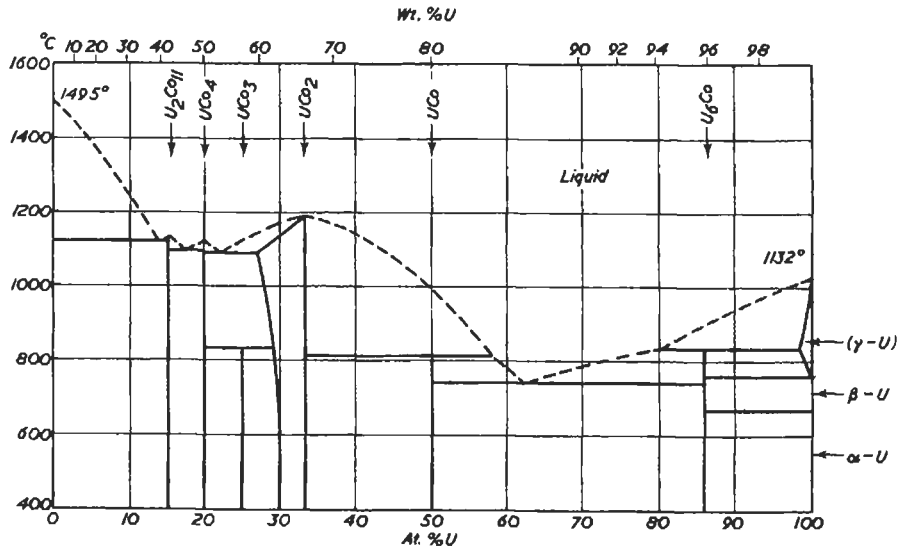

Co–Ta
Wt. %Ta
°C
Liquid
Co3Ta
γ-Co2Ta
(Co2Ta 0·8)
Co2Ta
1593°
1495°
1276°
13·5
α
β-Co2Ta
Magn. transformation
1033°
~990°
α-Co2Ta
At %Ta


Co–Te
Wt. %Te
°C
1495°
Liquid
CoTe
CoTe2
~1010°
960°
~41
γ
749°
449°
At. %Te

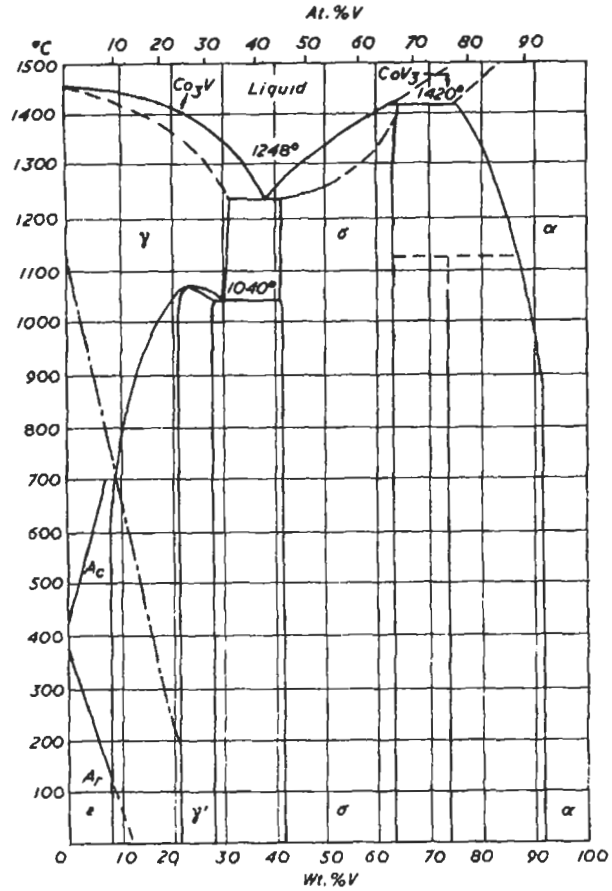
Co–Ti


Wt %Ti
°C
5 10 20 30 40 50 60 70 80 90
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
1660°
Liquid
1495°
β-TiCo2
γ(Co3Ti)
α-TiCo2
TiCo
Ti2Co
?
~1200°
19 5
~1250°
12 8
~1170°
~16
22
β-Co
1055 ± 5°
1020 ± 5°
~77
85 5
β-Ti
γ
685 ± 10°
~92
α-Ti
0 10 20 30 40 50 60 70 80 90 100
At. %Ti

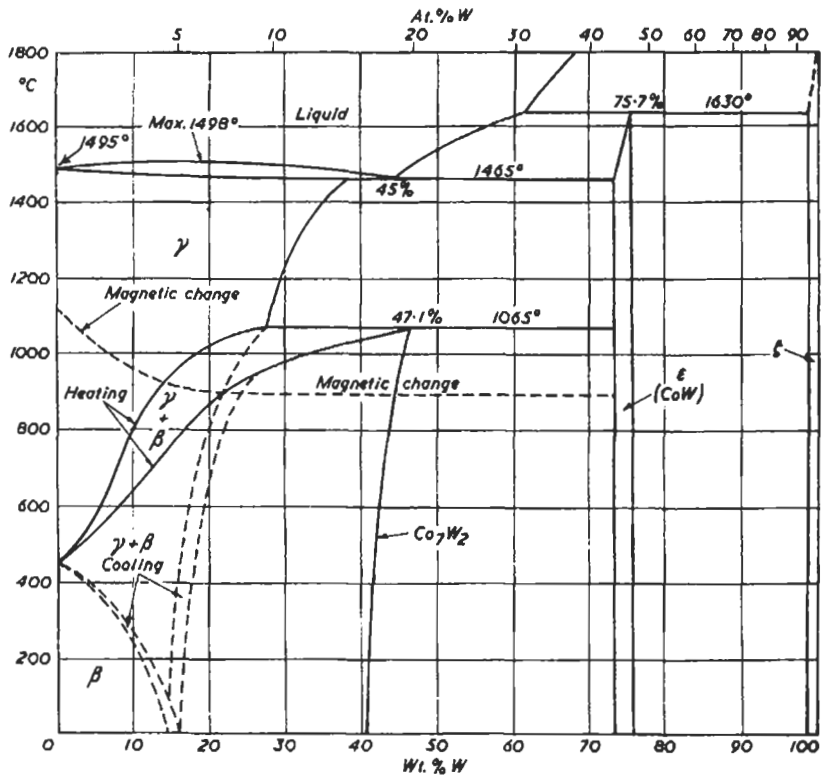
Co–U


Wt. %U
°C
10 20 30 40 50 60 70 80 90 92 94 96 98
1600
1400
1200
1000
800
600
400
1495°
U2Co11
UCo4
UCo3
UCo2
UCo
U6Co
Liquid
1132°
(γ-U)
β-U
α-U
0 10 20 30 40 50 60 70 80 90 100
At. %U

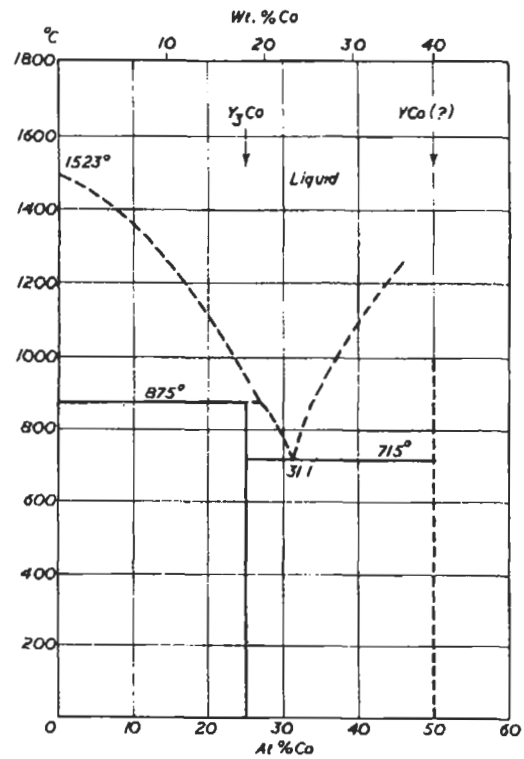
Co–V


At. %V
°C
10 20 30 40 50 60 70 80 90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Co3V
Liquid
CoV3
1420°
1248°
1040°
γ
σ
α
Ac
Ar
ε
γ'
σ
α
10 20 30 40 50 60 70 80 90 100
Wt. %V

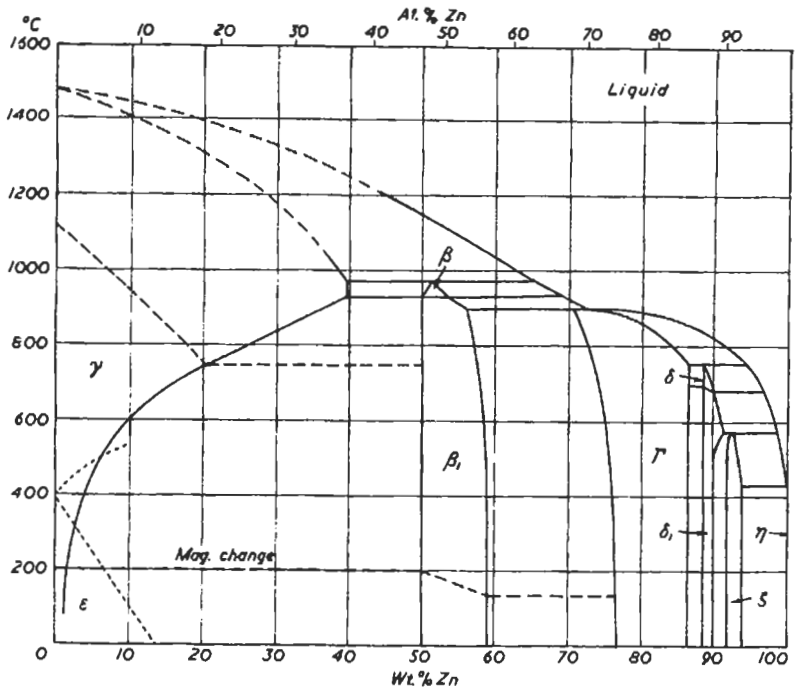
Co–W


At.% W
5
10
20
30
40
50
60
70
80
90
1800
°C
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
70
80
90
100
Wt. % W
Liquid
Max. 1498°
1495°
1465°
45%
75·7%
1630°
γ
Magnetic change
47·1%
1065°
Heating
γ + β
β
Magnetic change
ε
(CoW)
ζ
Co7W2
γ + β
Cooling
β

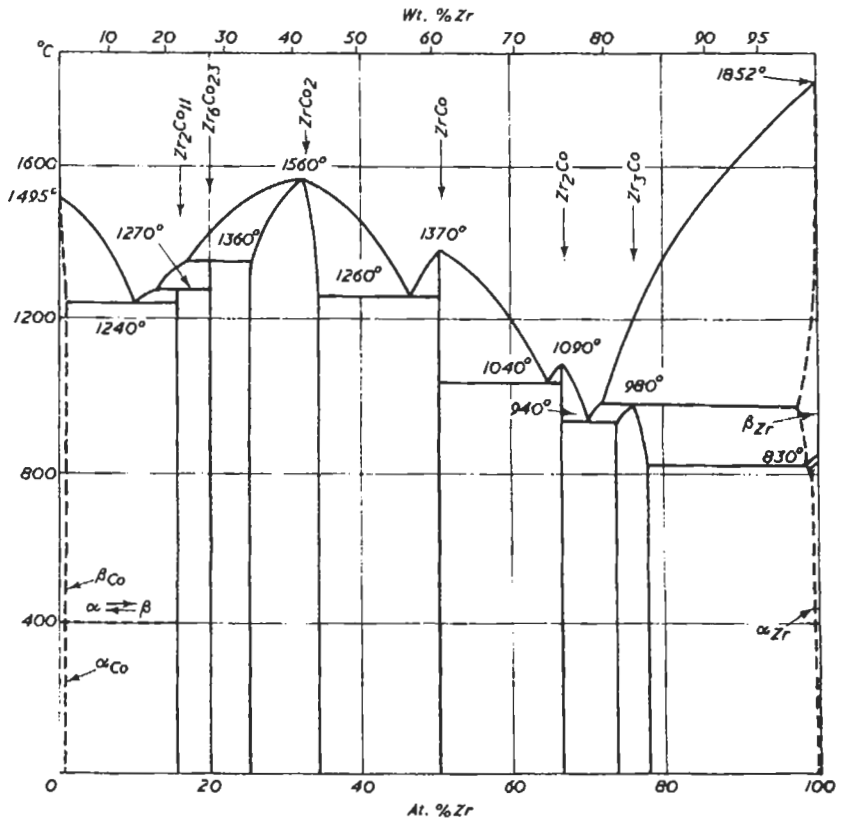
Co–Y


Wt. % Co
°C
10
20
30
40
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
50
60
At % Co
Y3Co
YCo (?)
Liquid
1523°
875°
715°
31·1

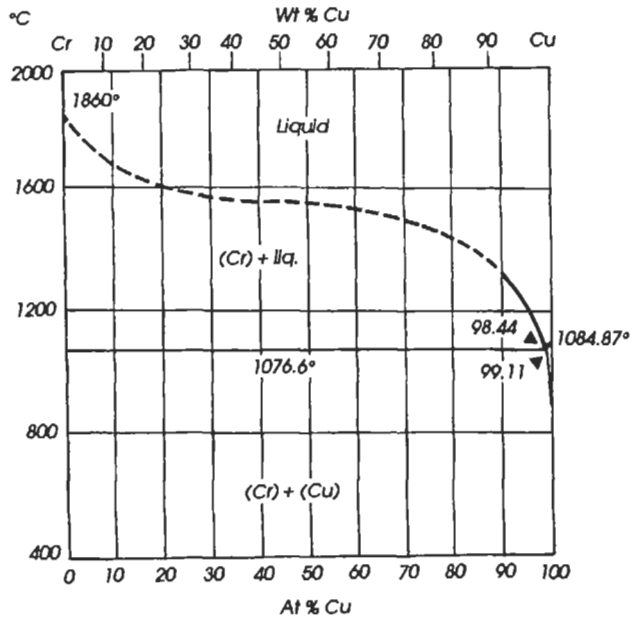
Co–Zn


°C
At. % Zn
Liquid
β
γ
δ
Γ
β1
δ1
η
ζ
Mag. change
ε
Wt.% Zn

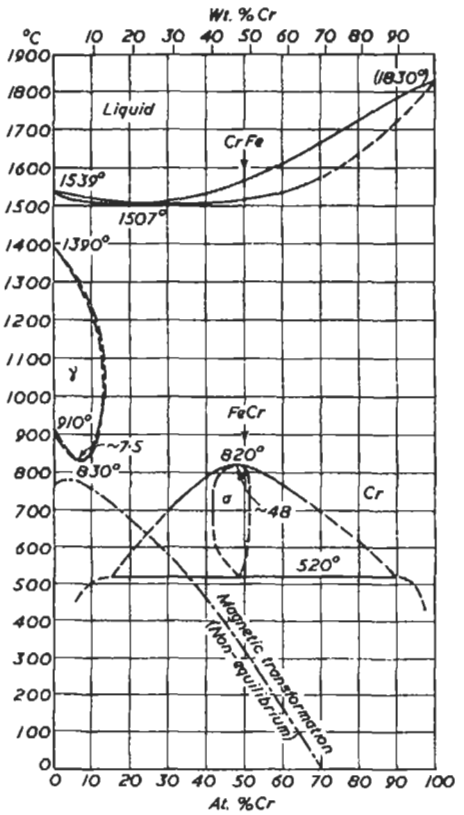
Co–Zr


Wt. % Zr
°C
Zr2Co11
Zr6Co23
ZrCo2
ZrCo
Zr2Co
Zr3Co
1852°
1560°
1495°
1270°
1360°
1370°
1260°
1240°
1090°
1040°
980°
940°
βZr
830°
βCo
α ⇄ β
αCo
αZr
At. %Zr

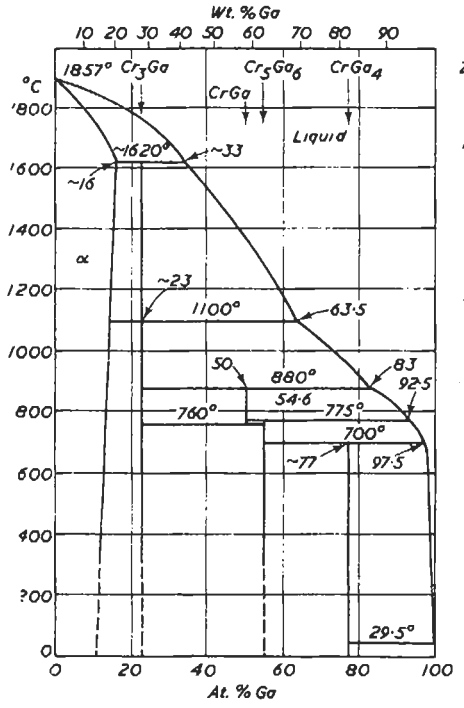
Cr–Cu


°C
Wt % Cu
Cr 10 20 30 40 50 60 70 80 90 Cu
2000
1600
1200
800
400
1860°
Liquid
(Cr) + liq.
98.44
1084.87°
99.11
1076.6°
(Cr) + (Cu)
0 10 20 30 40 50 60 70 80 90 100
At % Cu

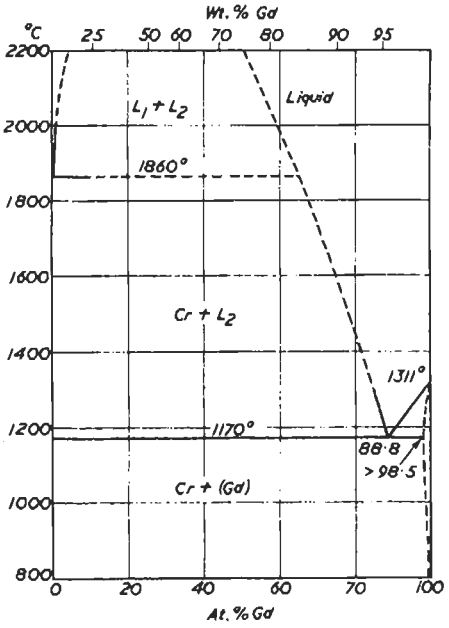
Cr–Fe


Wt. % Cr
°C 10 20 30 40 50 60 70 80 90
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Liquid
(1830°)
CrFe
1539°
1507°
1390°
γ
910°
~7.5
830°
FeCr
820°
σ
~48
Cr
520°
Magnetic transformation
(Non-equilibrium)
0 10 20 30 40 50 60 70 80 90 100
At. %Cr

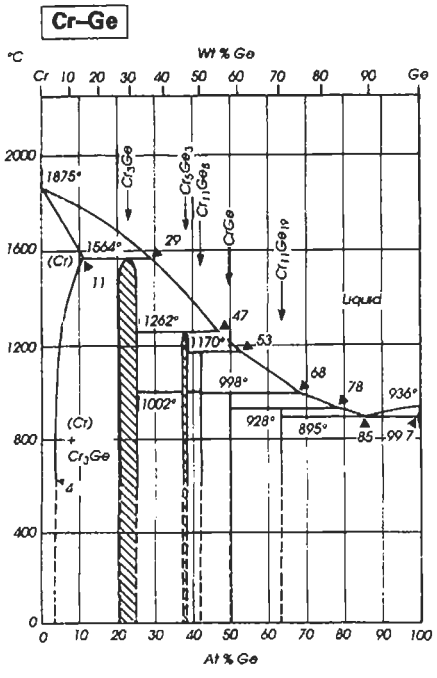
Cr–Ga



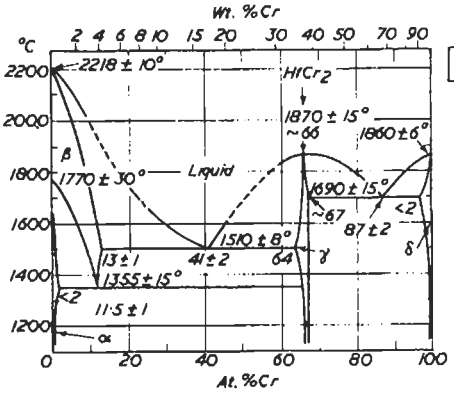
Cr–Gd



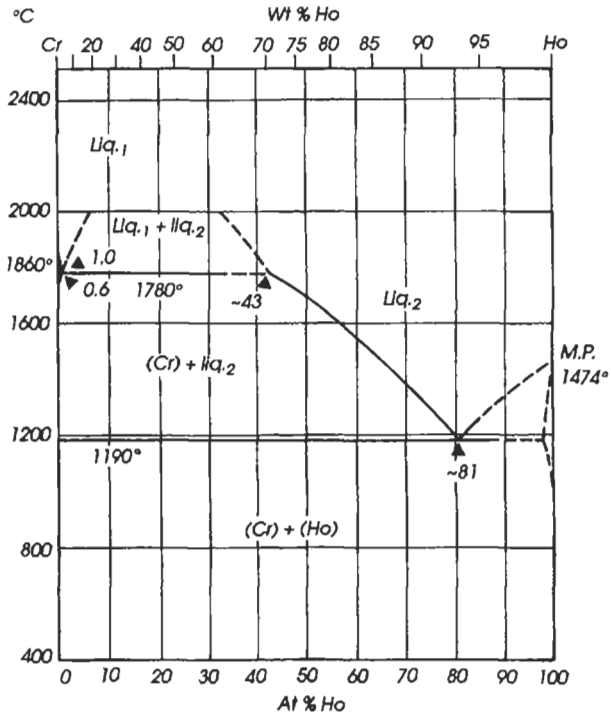
Cr–Ge



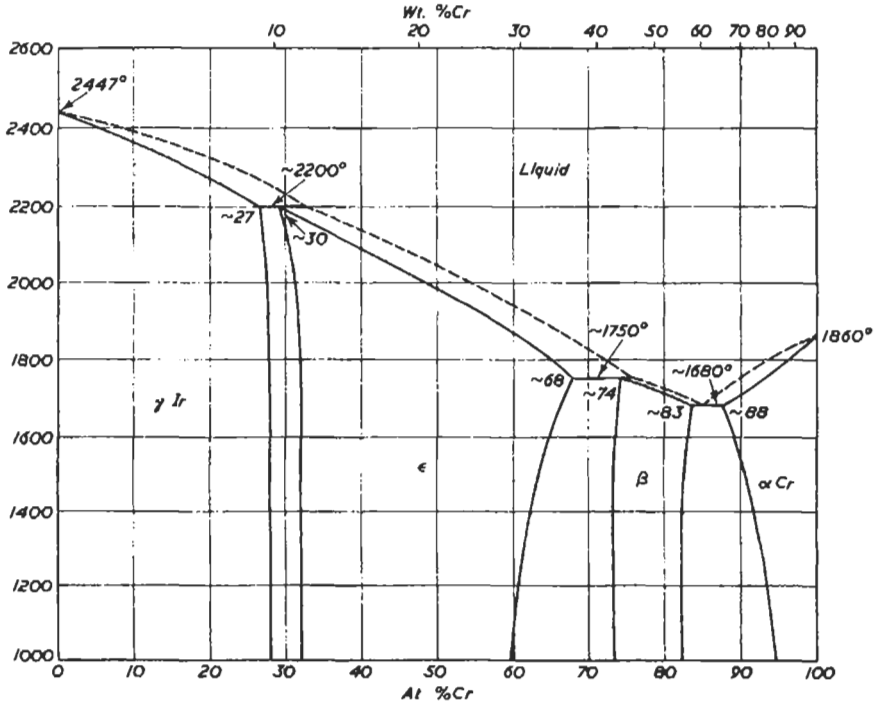
Cr–Hf



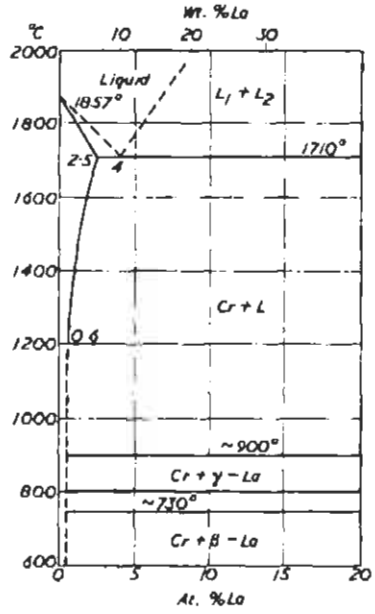
Cr–Ho


°C
Wt % Ho
Cr 20 40 50 60 70 75 80 85 90 95 Ho
2400
2000
1860°
1600
1200
800
400
Liq.1
Liq.1 + liq.2
1.0
0.6
1780°
~43
Liq.2
M.P.
1474°
(Cr) + liq.2
1190°
~81
(Cr) + (Ho)
0 10 20 30 40 50 60 70 80 90 100
At % Ho

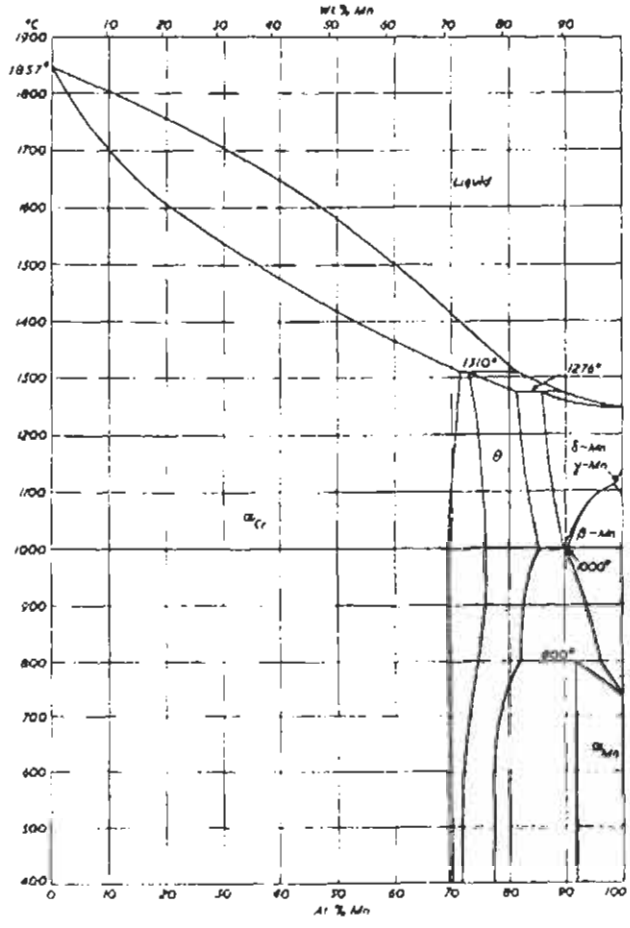
Cr–Ir


Wt. %Cr
10 20 30 40 50 60 70 80 90
2600
2400
2200
2000
1800
1600
1400
1200
1000
2447°
~2200°
Liquid
~27
~30
~1750°
1860°
~68
~74
~1680°
~83
~88
γ Ir
ε
β
α Cr
0 10 20 30 40 50 60 70 80 90 100
At %Cr

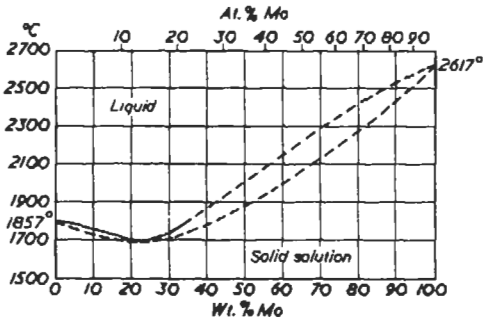
Cr–La


Wt. %La
°C
10
20
30
2000
1800
1600
1400
1200
1000
800
600
Liquid
1857°
$L_1 + L_2$
2·5
4
1710°
Cr + L
0·6
~900°
Cr + γ – La
~730°
Cr + β – La
0
5
10
15
20
At. %La

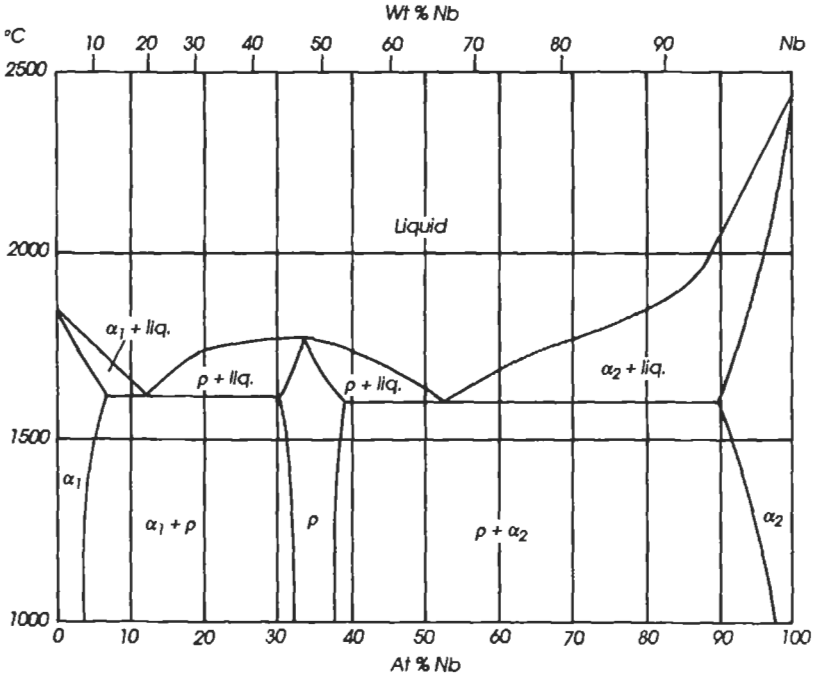
Cr–Mn


Wt % Mn
°C
10
20
30
40
50
60
70
80
90
1900
1857°
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
Liquid
1310°
1276°
θ
δ-Mn
γ-Mn
β-Mn
α_Cr
α_Mn
0
10
20
30
40
50
60
70
80
90
100
At % Mn

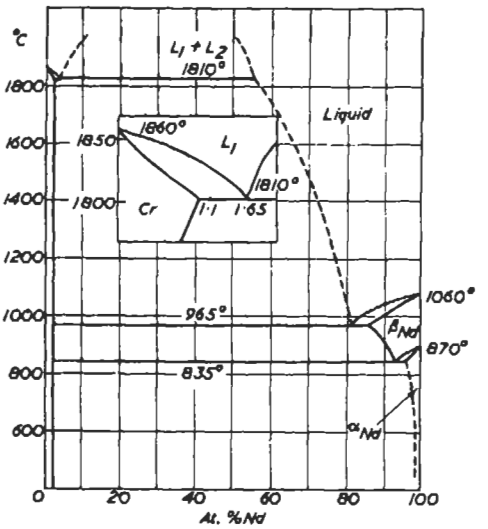
Cr–Mo



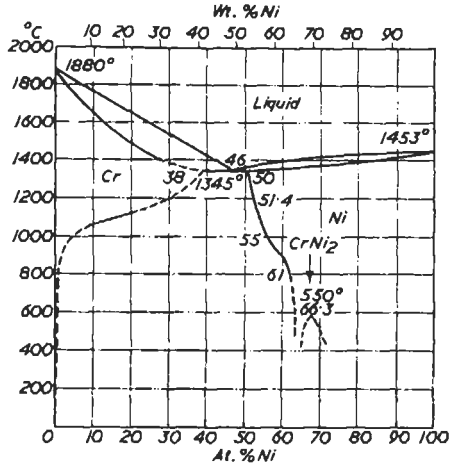
Cr–Nb



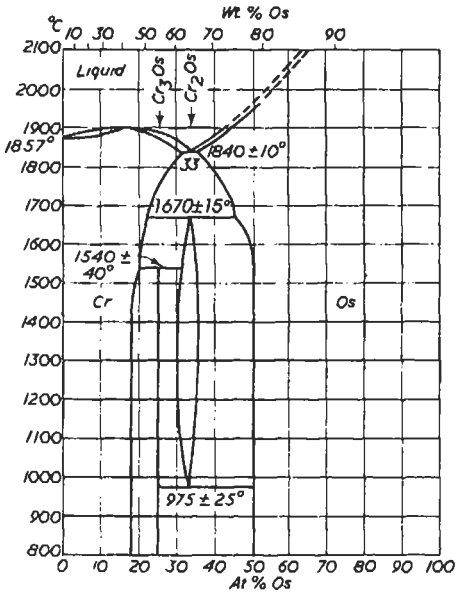
Cr–Nd



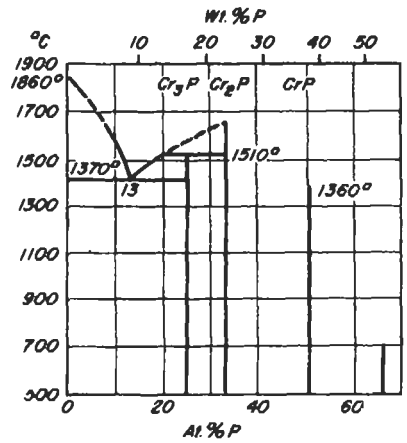
Cr–Ni



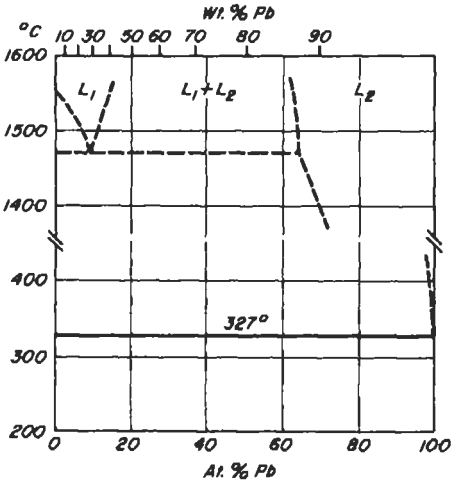
Cr–Os



Cr–P



Cr–Pb

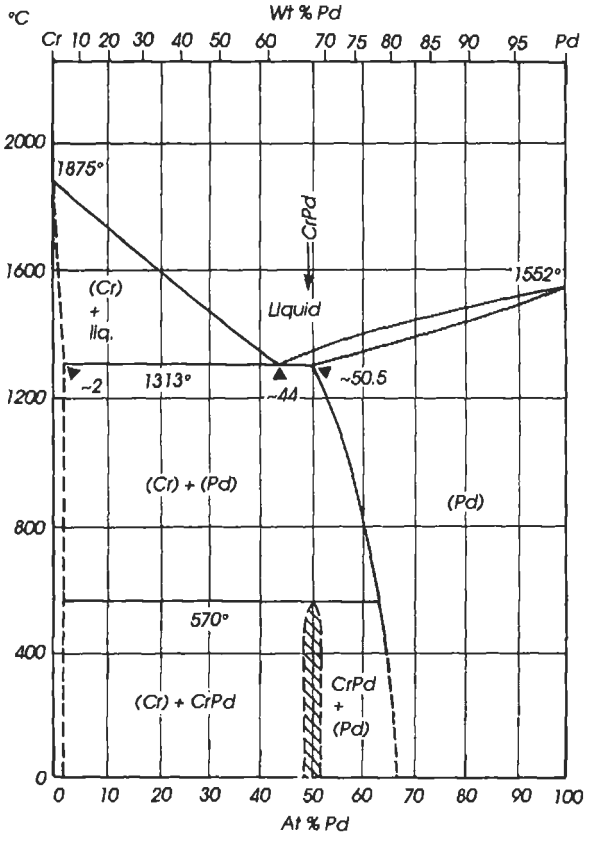


*Sol Cr in liq Pb 908/1210°C

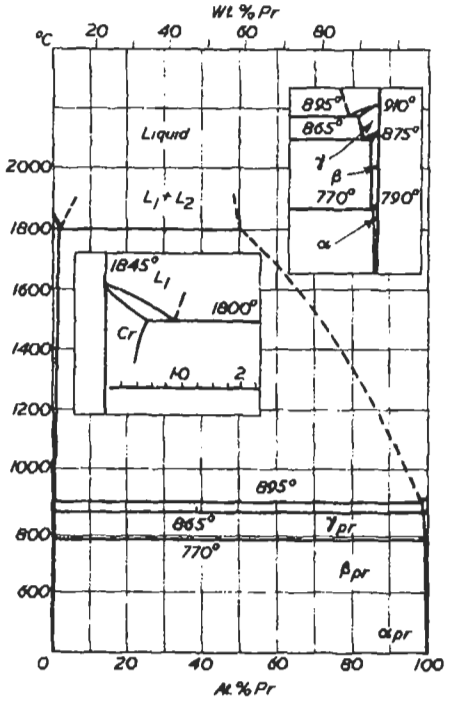
$\log_{10}$ (At % Cr) = 4 315 − 6717/T°K

M.p. Cr=1860°C

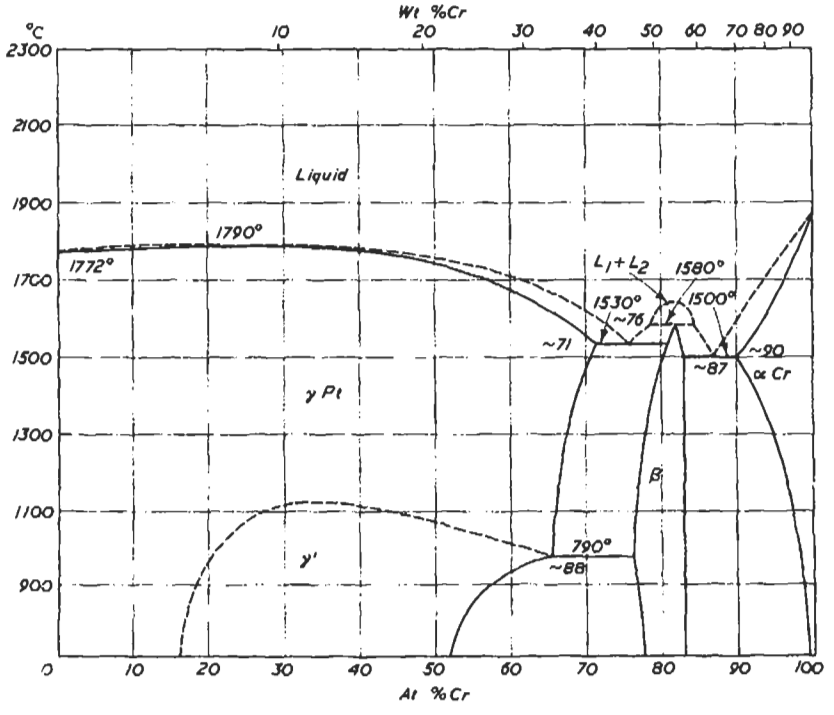
Cr–Pd



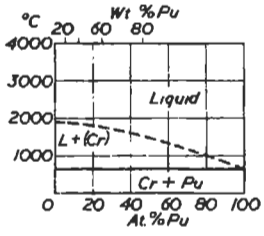
Cr–Pr


Wt % Pr
°C
20
40
60
80
Liquid
$L_1 + L_2$
1845°
L_1
1800°
Cr
1.0
2
895°
865°
770°
910°
875°
790°
γ
β
α
2000
1800
1600
1400
1200
1000
800
600
γ_{pr}
β_{pr}
α_{pr}
0
20
40
60
80
100
At % Pr

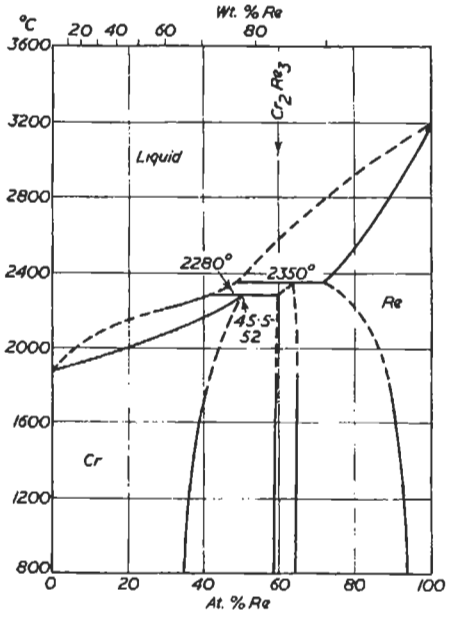
Cr–Pt


Wt %Cr
°C
10
20
30
40
50
60
70
80
90
2300
2100
1900
1700
1500
1300
1100
900
Liquid
1790°
1772°
$L_1 + L_2$
1580°
1530°
~76
1500°
~71
~87
~90
α Cr
γ Pt
β
γ'
790°
~88
0
10
20
30
40
50
60
70
80
90
100
At %Cr

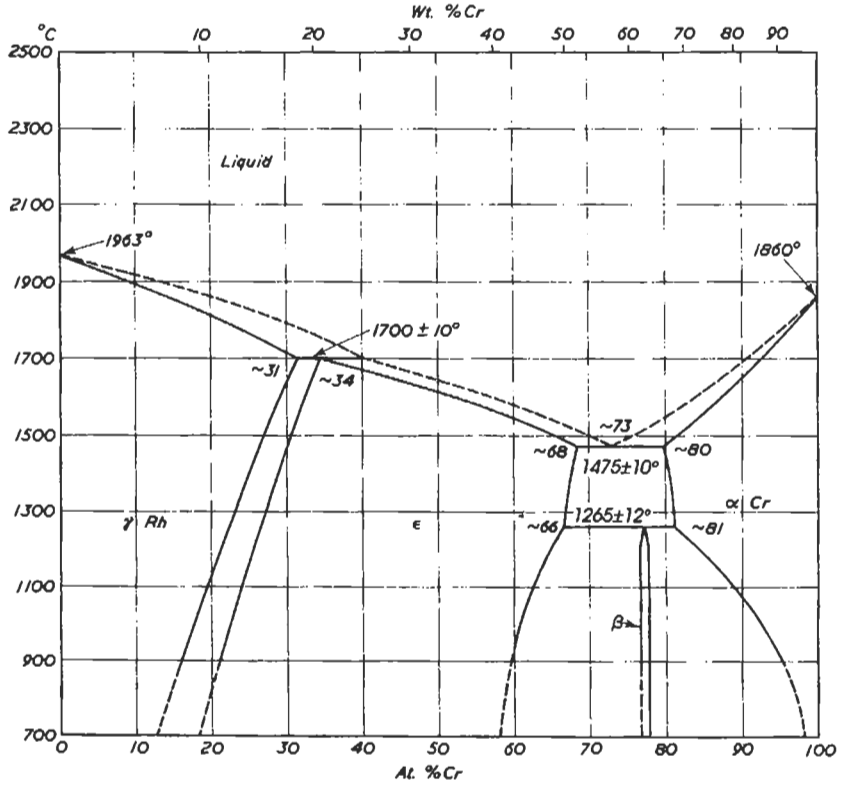
Cr–Pu



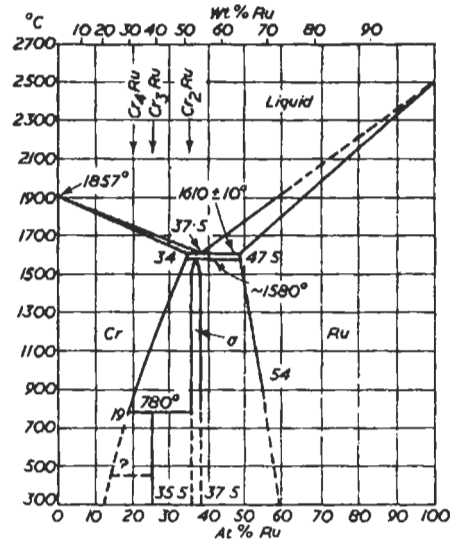
Cr–Re



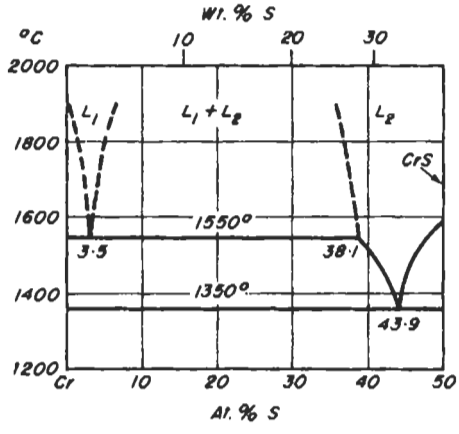
Cr–Rh



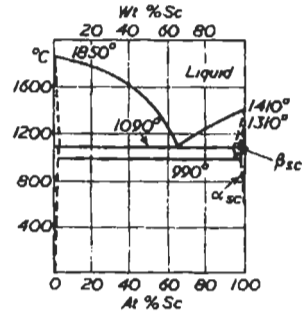
Cr–Ru



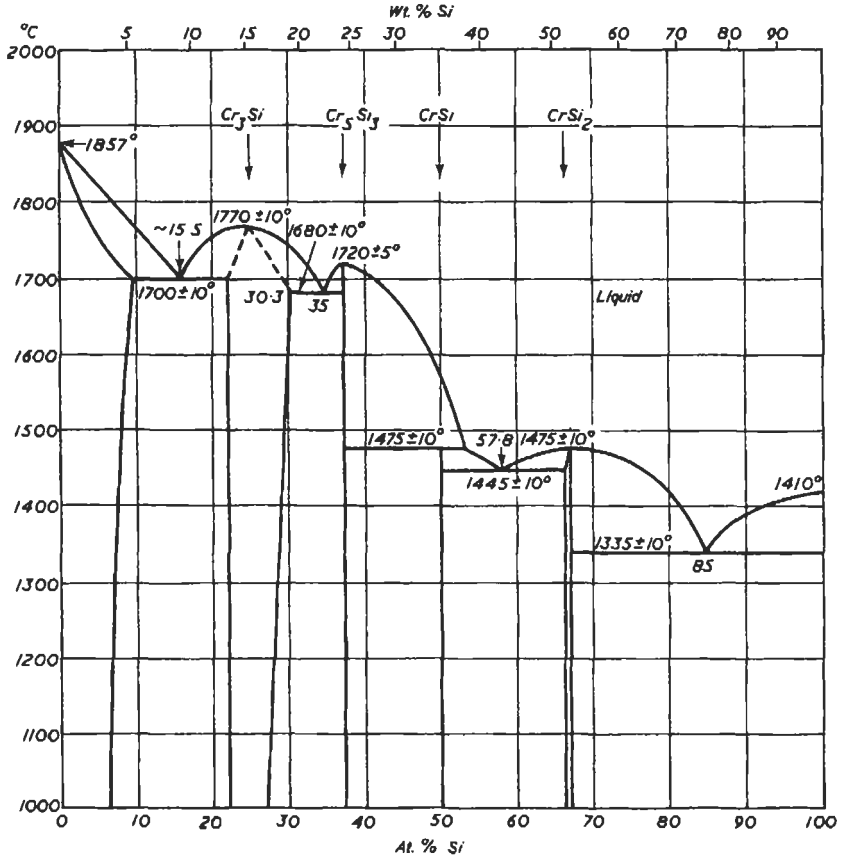
Cr–S



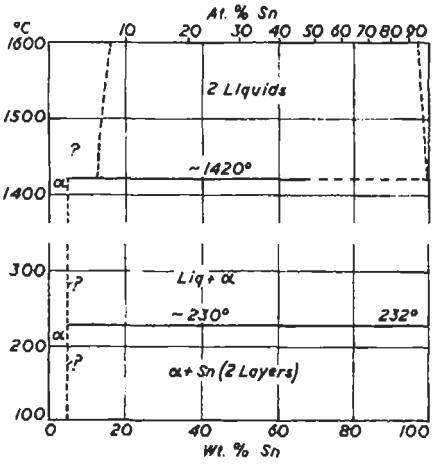
Cr–Sc



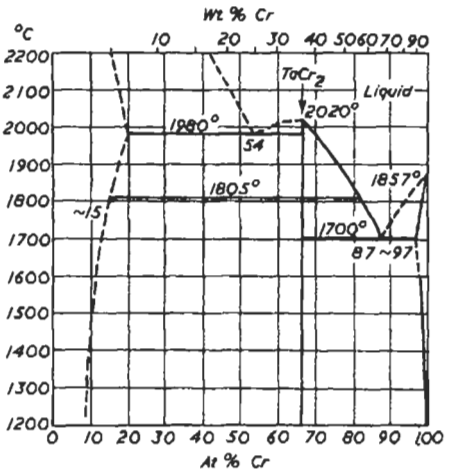
Cr–Si


Wt. % Si
°C
5 10 15 20 25 30 40 50 60 70 80 90
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Cr_3Si
Cr_5Si_3
CrSi
$CrSi_2$
1857°
~15 S
1770±10°
1680±10°
1720±5°
1700±10°
30·3
35
Liquid
1475±10°
57·8
1475±10°
1445±10°
1410°
1335±10°
85
0 10 20 30 40 50 60 70 80 90 100
At. % Si

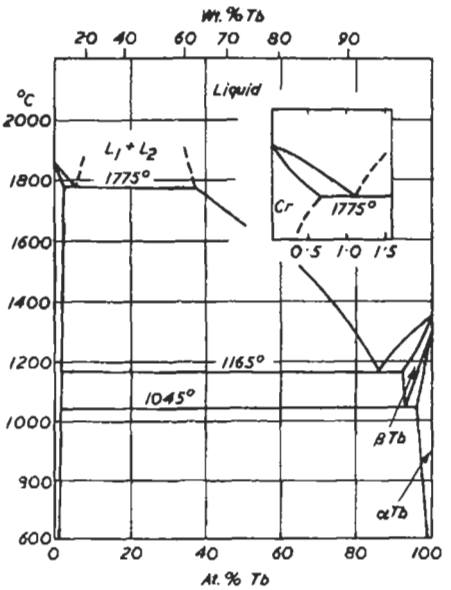
Cr–Sn


At. % Sn
°C
10 20 30 40 50 60 70 80 90
1600
1500
1400
300
200
100
2 Liquids
?
~1420°
α
Liq + α
?
~230°
232°
α
?
α + Sn (2 Layers)
0 20 40 60 80 100
Wt. % Sn

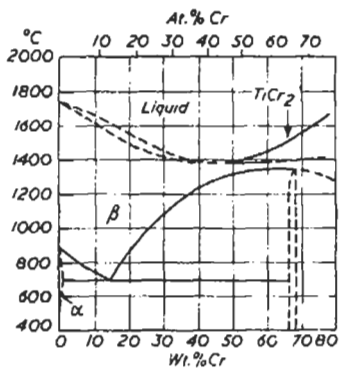
Cr–Ta



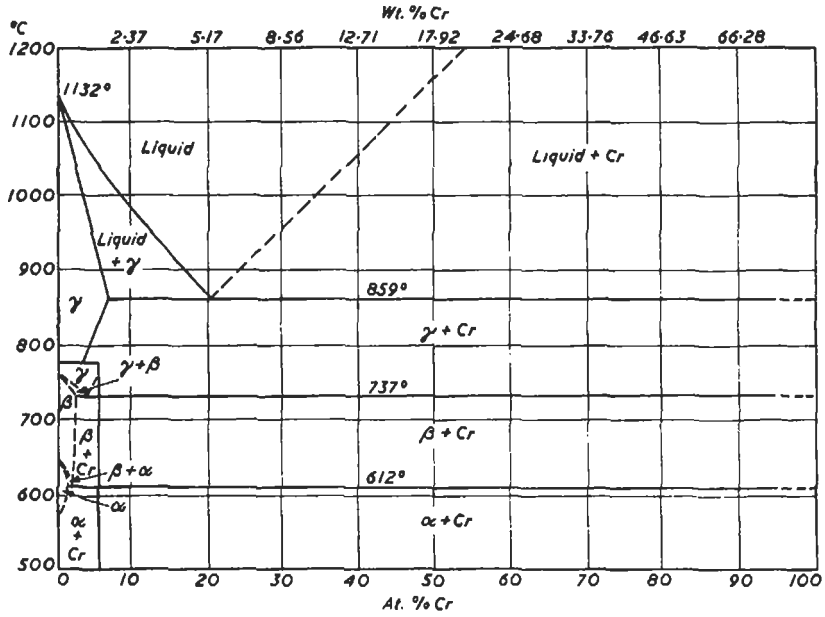
Cr–Tb



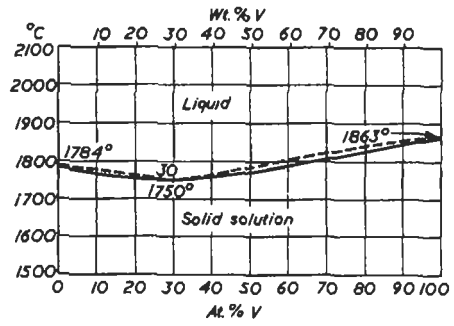
Cr–Ti



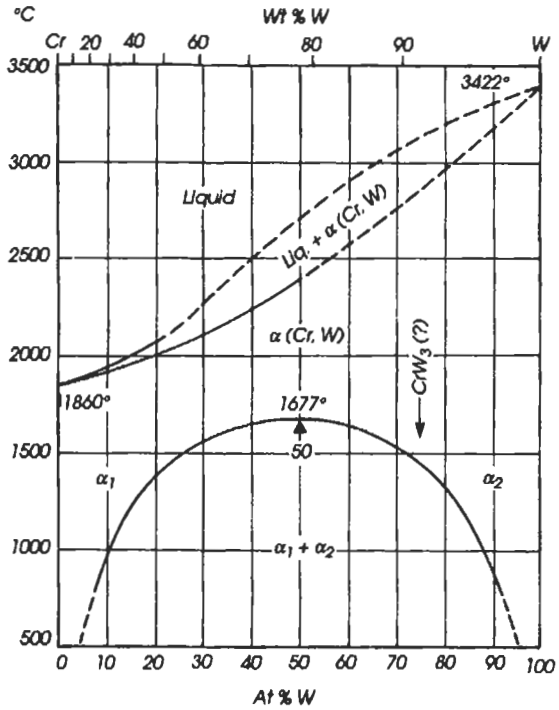
Cr–U


Wt. % Cr
°C
2·37
5·17
8·56
12·71
17·92
24·68
33·76
46·63
66·28
1200
1100
1000
900
800
700
600
500
1132°
Liquid
Liquid + Cr
Liquid + γ
γ
859°
γ + Cr
γ + β
737°
β
β + Cr
β + α
612°
α
α + Cr
0
10
20
30
40
50
60
70
80
90
100
At. % Cr

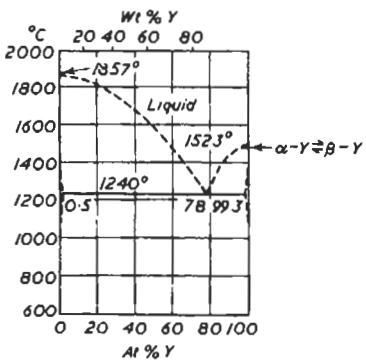
Cr–V


Wt. % V
°C
10
20
30
40
50
60
70
80
90
2100
2000
1900
1800
1700
1600
1500
Liquid
1863°
1784°
1750°
Solid solution
0
10
20
30
40
50
60
70
80
90
100
At. % V

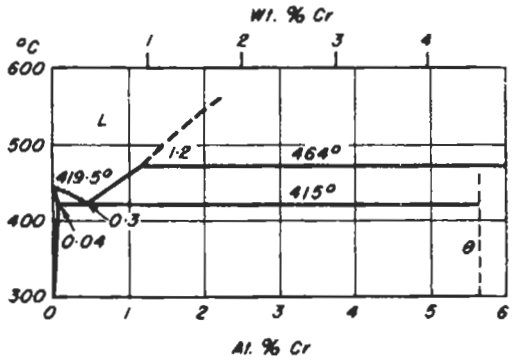
Cr–W


°C
Wt % W
Cr 20 40 60 80 90 W
3500
3000
2500
2000
1500
1000
500
3422°
Liquid
Liq. + α (Cr, W)
α (Cr, W)
CrW3 (?)
1860°
1677°
50
α1
α2
α1 + α2
0 10 20 30 40 50 60 70 80 90 100
At % W

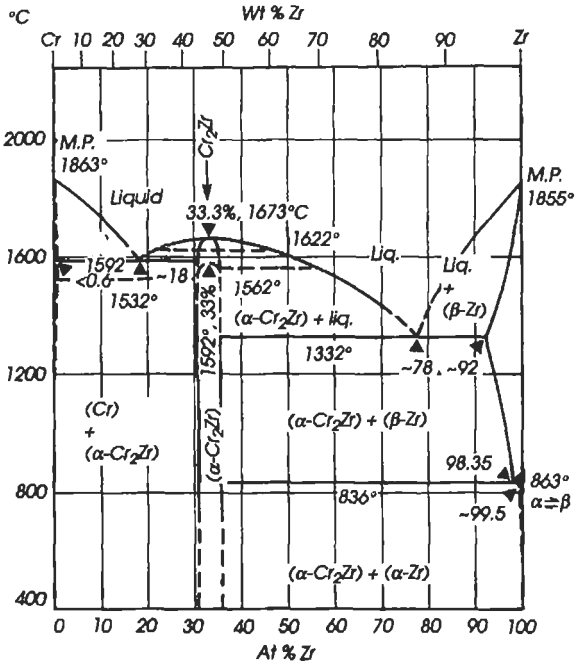
Cr–Y


°C
Wt % Y
20 40 60 80
2000
1800
1600
1400
1200
1000
800
600
1857°
Liquid
1523°
α-Y ⇌ β-Y
1240°
0·5
78
99·3
0 20 40 60 80 100
At % Y

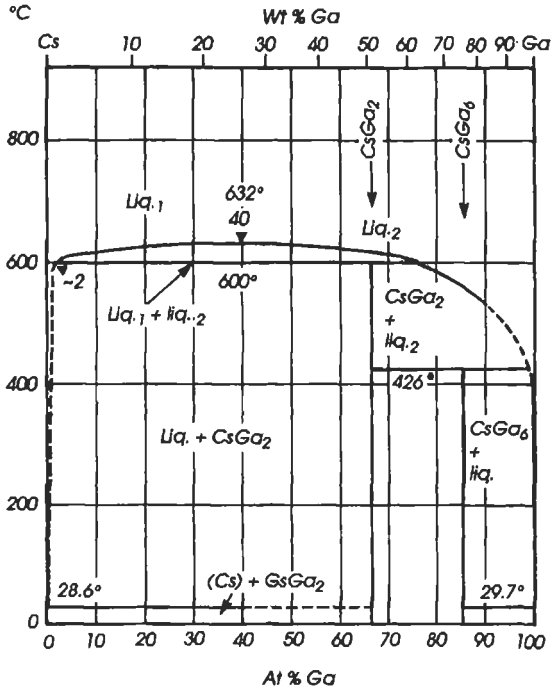
Cr–Zn


Wt. % Cr
°C
1 2 3 4
600
500
400
300
L
1·2
464°
419·5°
415°
0·3
0·04
θ
0 1 2 3 4 5 6
At. % Cr

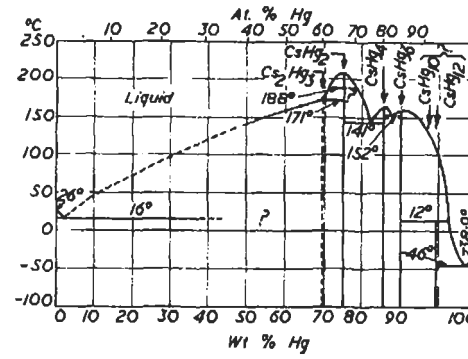
Cr–Zr


°C
Wt % Zr
Cr 10 20 30 40 50 60 70 80 90 Zr
2000
1600
1200
800
400
M.P. 1863°
Liquid
33.3%, 1673°C
Cr_2Zr
1622°
Liq.
M.P. 1855°
1592°
<0.6
~18
1532°
1562°
(α-Cr_2Zr) + liq.
1592°, 33%
Liq. + (β-Zr)
1332°
~78, ~92
(Cr) + (α-Cr_2Zr)
(α-Cr_2Zr) + (β-Zr)
98.35
863° α⇌β
836°
~99.5
(α-Cr_2Zr) + (α-Zr)
0 10 20 30 40 50 60 70 80 90 100
At % Zr

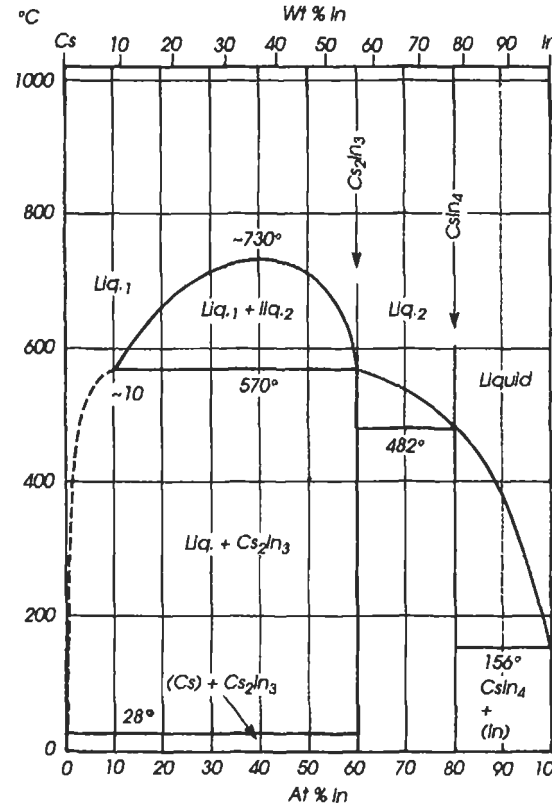
Cs–Ga


°C
Wt % Ga
Cs 10 20 30 40 50 60 70 80 90 Ga
800
600
400
200
0
$CsGa_2$
$CsGa_6$
Liq.1
632°
40
Liq.2
~2
600°
Liq.1 + liq.2
$CsGa_2$ + liq.2
426
Liq. + $CsGa_2$
$CsGa_6$ + liq.
28.6°
(Cs) + $GsGa_2$
29.7°
0 10 20 30 40 50 60 70 80 90 100
At % Ga

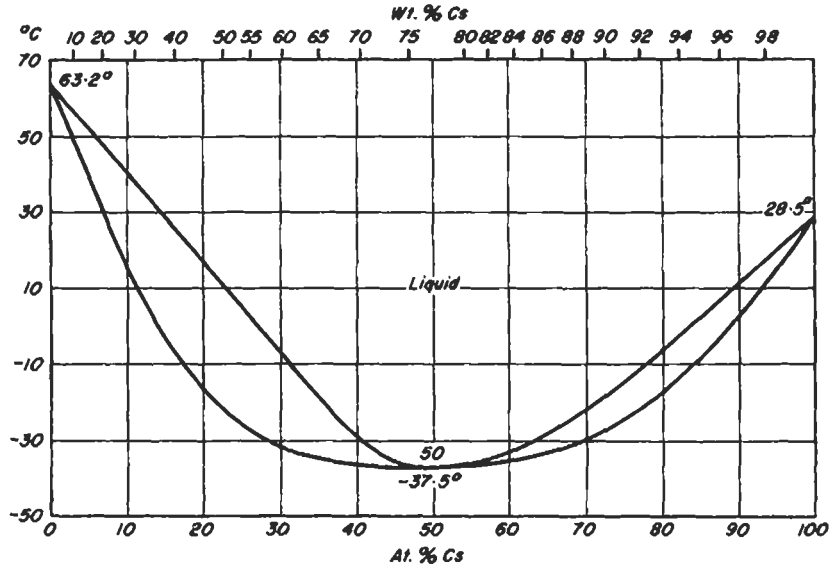
Cs–Hg


°C
At. % Hg
10 20 30 40 50 60 70 80 90
250
200
150
100
50
0
-50
-100
Liquid
188°
171°
152°
28°
16°
?
12°
-38.9°
0 10 20 30 40 50 60 70 80 90 100
Wt % Hg

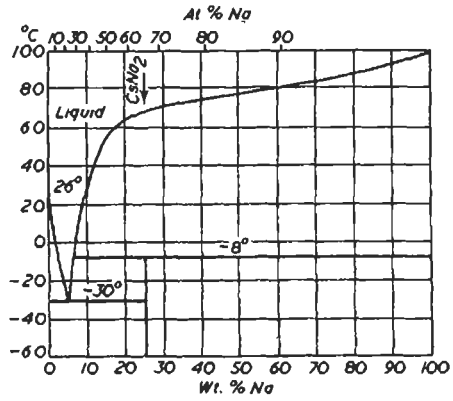
Cs–In


°C
Wt % In
Cs 10 20 30 40 50 60 70 80 90 In
1000
800
600
400
200
0
Cs_2In_3
$CsIn_4$
~730°
Liq.1
Liq.1 + liq.2
Liq.2
Liquid
~10
570°
482°
Liq. + Cs_2In_3
(Cs) + Cs_2In_3
28°
156°
$CsIn_4$
+
(In)
0 10 20 30 40 50 60 70 80 90 100
At % In

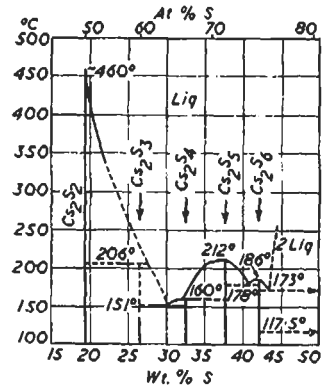
Cs–K



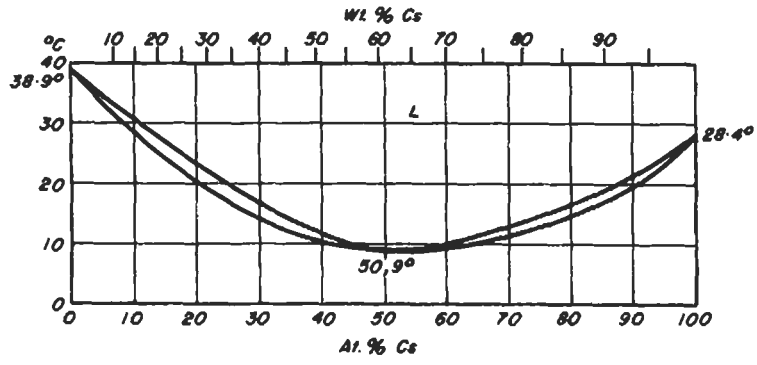
Cs–Na



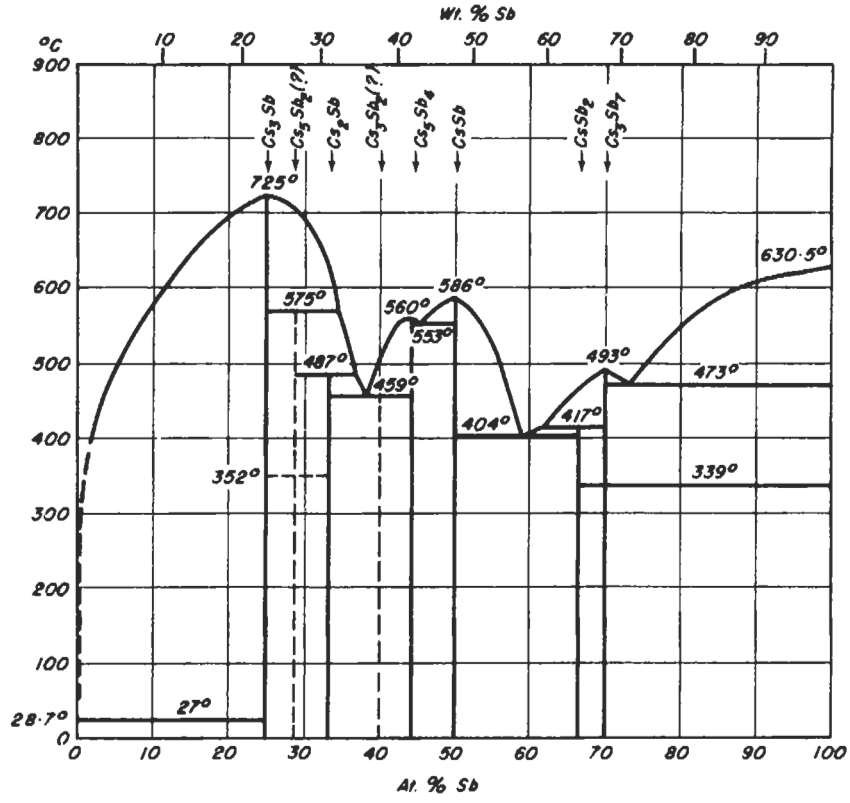
Cs–S



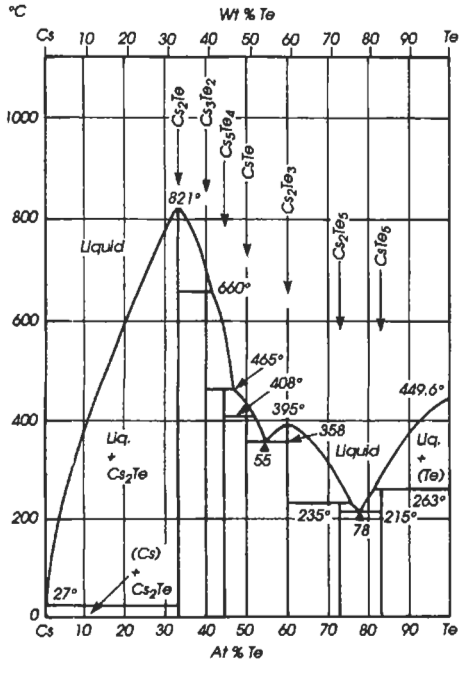
Cs–Rb



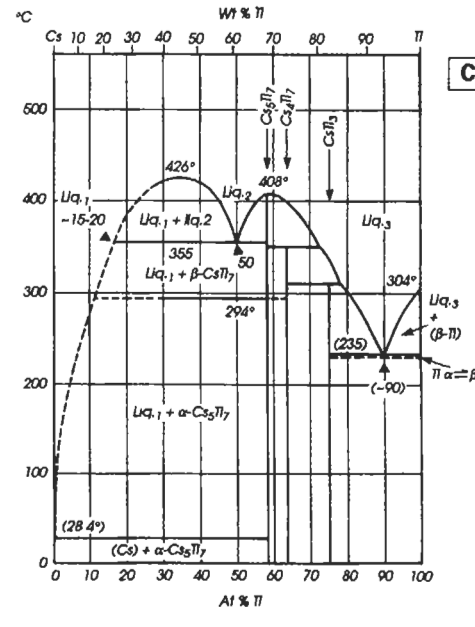
Cs–Sb



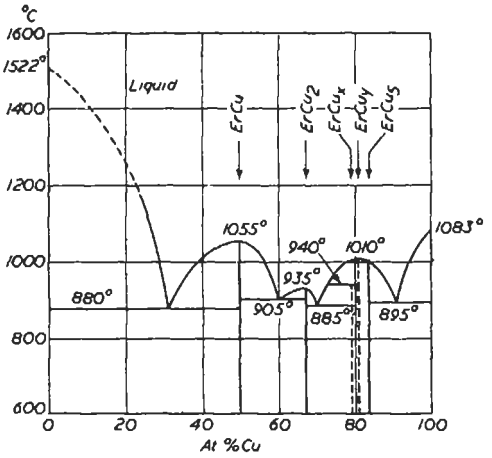
Cs–Tl



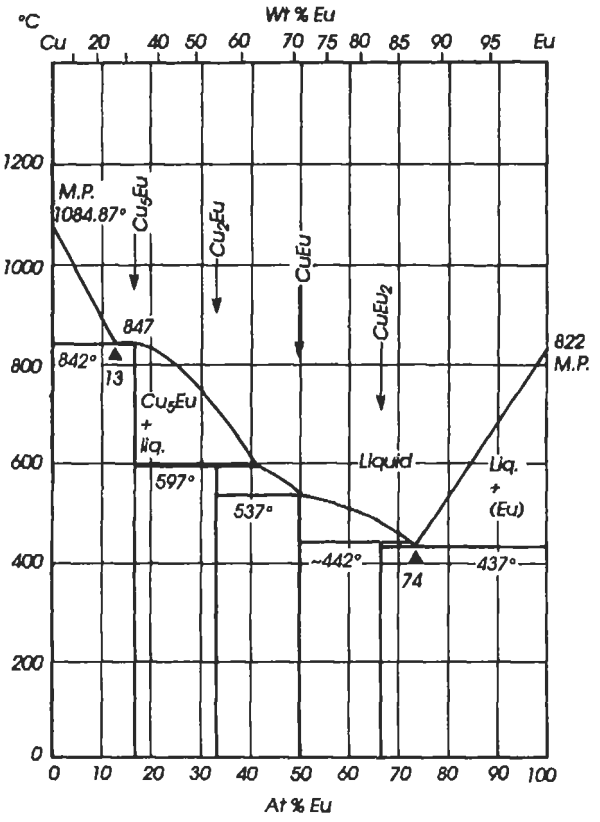
Cs–Te



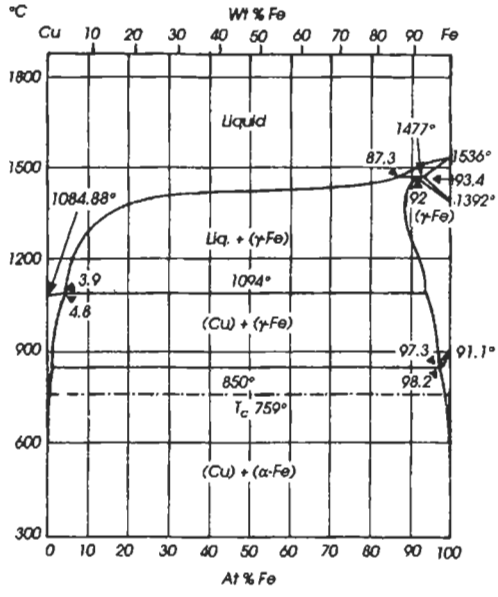
Cu–Er


°C
1600
1522°
1400
1200
1000
800
600
Liquid
Er-Cu
Er-Cu2
Er-Cux
Er-Cuy
Er-Cu5
1055°
940°
1010°
1083°
935°
880°
905°
885°
895°
0
20
40
60
80
100
At %Cu

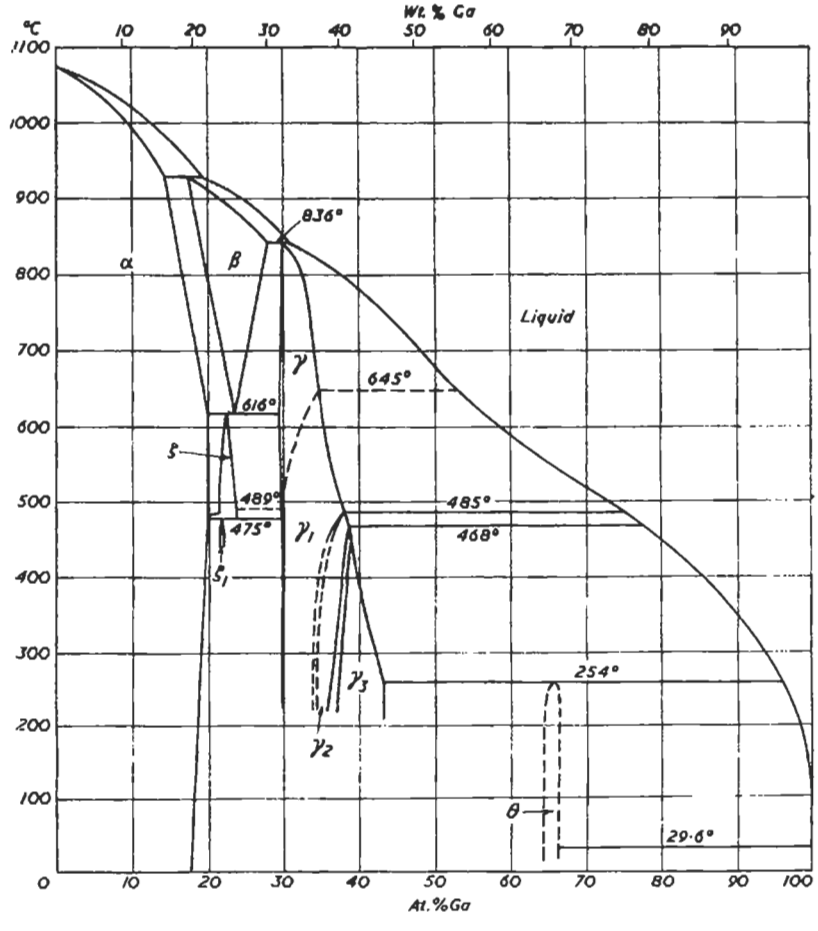
Cu–Eu


°C
Wt % Eu
Cu 20 40 50 60 70 75 80 85 90 95 Eu
1200
1000
800
600
400
200
0
M.P.
1084.87°
Cu5Eu
Cu2Eu
CuEu
CuEu2
847
842°
13
822
M.P.
Cu5Eu
+
liq.
597°
537°
Liquid
Liq.
+
(Eu)
~442°
437°
74
0 10 20 30 40 50 60 70 80 90 100
At % Eu

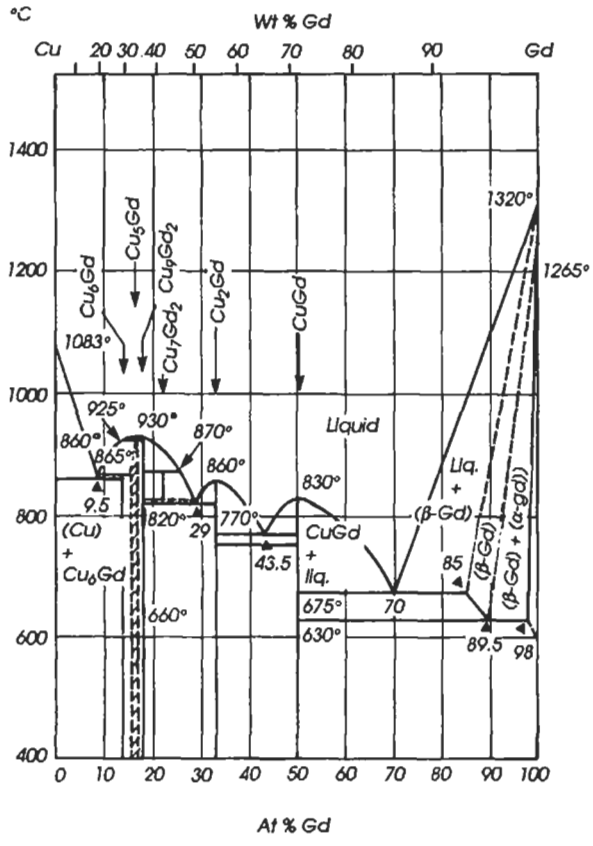
Cu–Fe


°C
Wt % Fe
Cu 10 20 30 40 50 60 70 80 90 Fe
1800
1500
1200
900
600
300
Liquid
1477°
87.3
1536°
93.4
92
1392°
(γ-Fe)
1084.88°
Liq. + (γ-Fe)
3.9
1094°
4.8
(Cu) + (γ-Fe)
97.3
91.1°
850°
98.2
T_c 759°
(Cu) + (α-Fe)
0 10 20 30 40 50 60 70 80 90 100
At % Fe

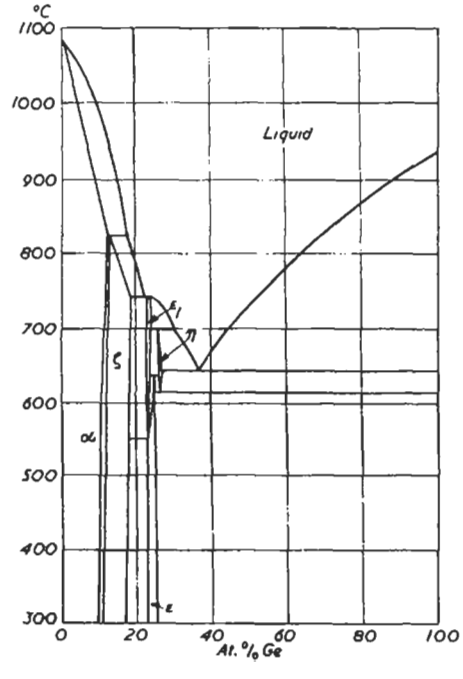
Cu–Ga


°C
Wt. % Ga
10 20 30 40 50 60 70 80 90
1100
1000
900
800
700
600
500
400
300
200
100
0
α
β
836°
Liquid
γ
645°
616°
ζ
489°
485°
475°
468°
γ_1
ζ_1
γ_3
254°
γ_2
θ
29·6°
10 20 30 40 50 60 70 80 90 100
At.%Ga

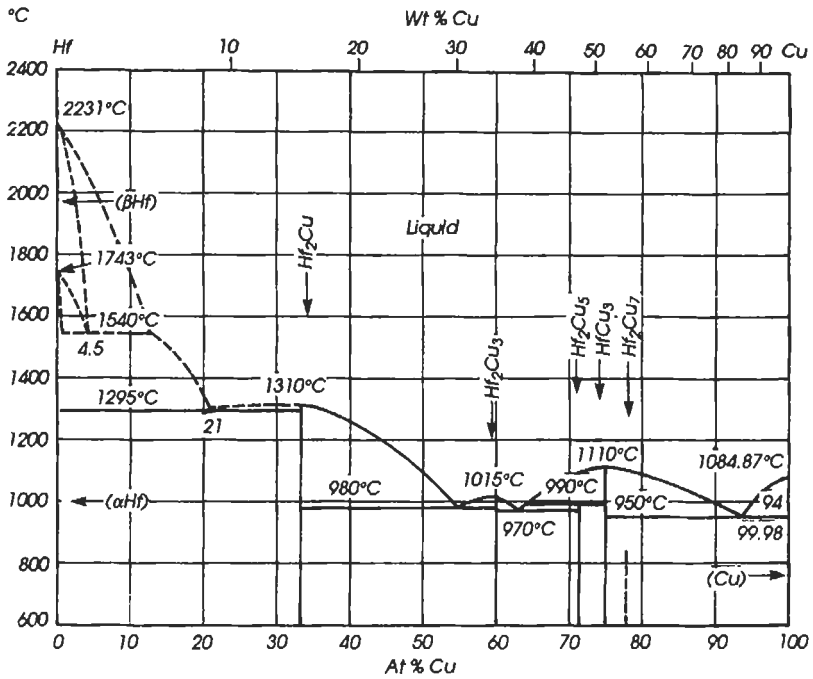
Cu–Gd


°C
Wt % Gd
Cu
20 30 40 50 60 70 80 90
Gd
1400
1200
1000
800
600
400
Cu_6Gd
Cu_5Gd
Cu_9Gd_2
Cu_7Gd_2
Cu_2Gd
CuGd
1320°
1265°
1083°
925°
930°
870°
860°
865°
860°
830°
Liquid
Liq. + (β-Gd)
(β-Gd) + (α-gd))
9.5
820°
29
770°
43.5
CuGd + liq.
85
(Cu) + Cu_6Gd
660°
675°
70
630°
89.5
98
0 10 20 30 40 50 60 70 80 90 100
At % Gd

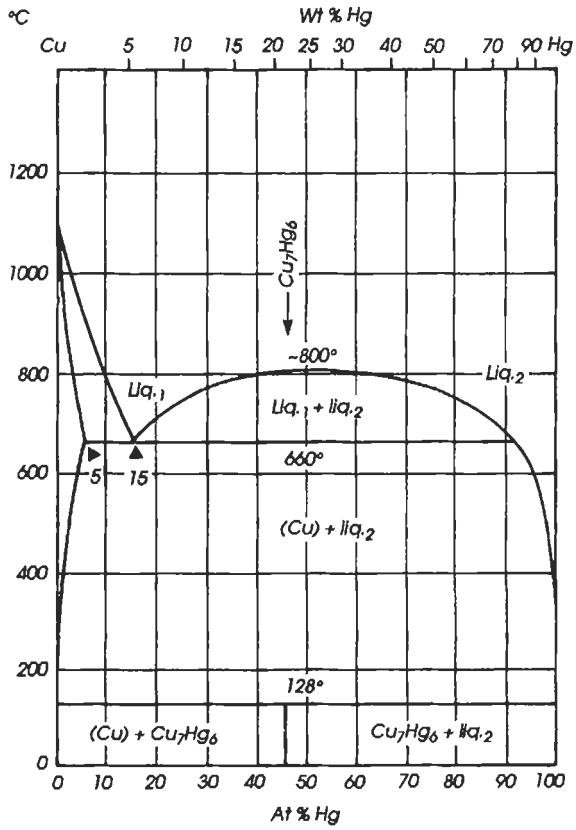
Cu–Ge


°C
1100
1000
900
800
700
600
500
400
300
Liquid
ξ
η
ζ
α
ε
0 20 40 60 80 100
At. % Ge

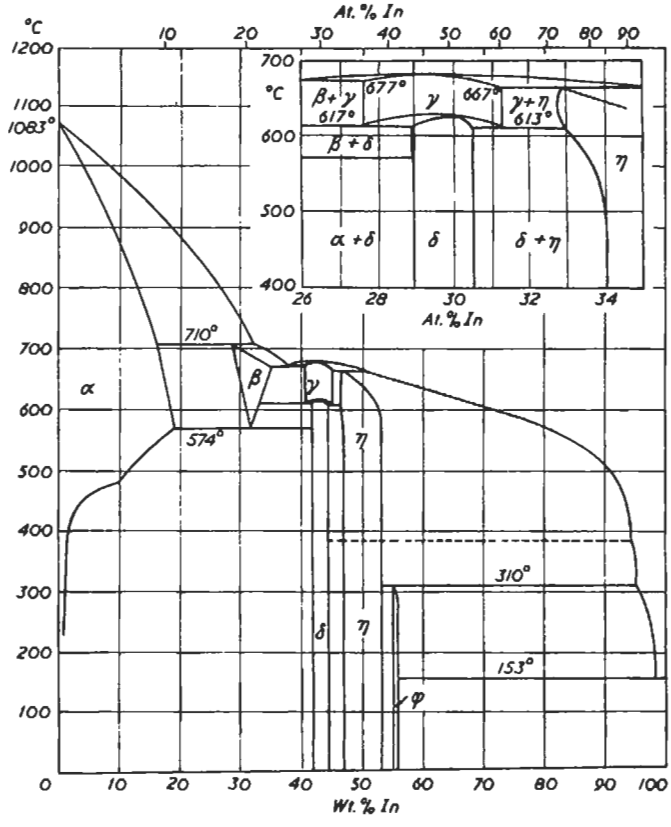
Cu–Hf


°C
Wt % Cu
Hf
Cu
2231°C
(βHf)
1743°C
1540°C
4.5
1295°C
21
1310°C
Liquid
Hf2Cu
Hf2Cu3
Hf2Cu5
HfCu3
Hf2Cu7
1110°C
1084.87°C
980°C
1015°C
990°C
950°C
94
970°C
99.98
(αHf)
(Cu)
At % Cu

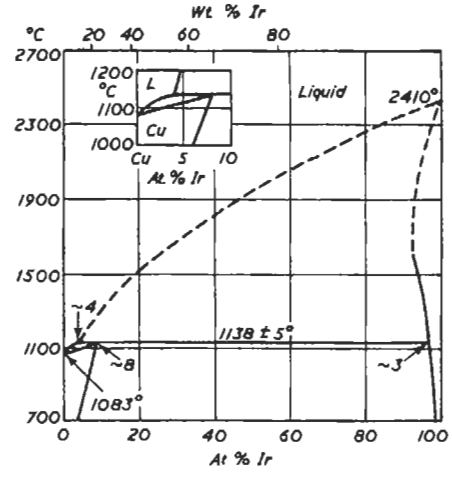
Cu–Hg


°C
Wt % Hg
Cu
Hg
Cu7Hg6
~800°
Liq.2
Liq.1
Liq.1 + liq.2
660°
5
15
(Cu) + liq.2
128°
(Cu) + Cu7Hg6
Cu7Hg6 + liq.2
At % Hg

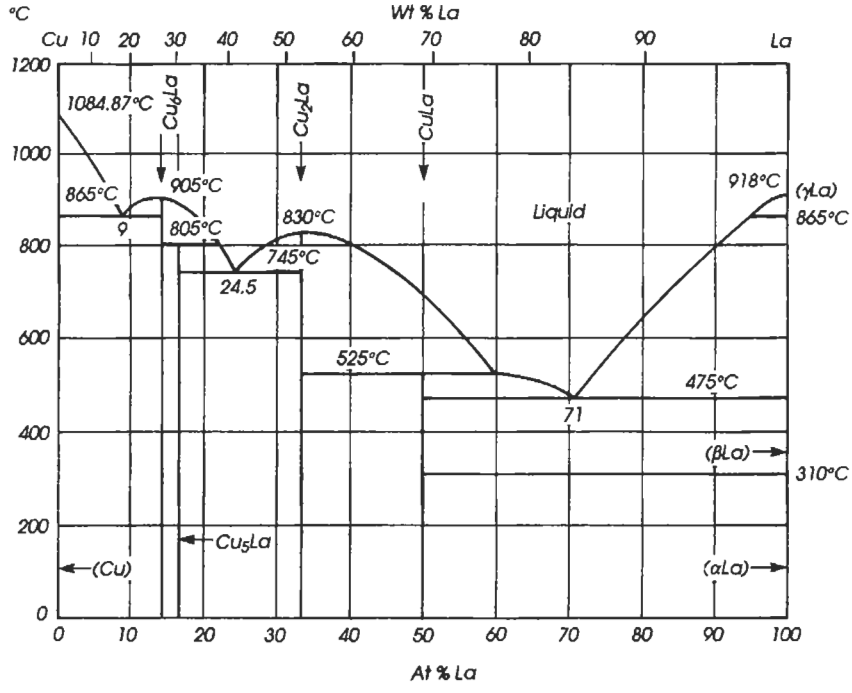
Cu–In


At. % In
°C
1200
1100
1083°
1000
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
70
80
90
100
Wt. % In
710°
574°
310°
153°
677°
617°
667°
613°
α
β
γ
δ
η
φ
α + δ
β + δ
γ + η
26
28
32
34

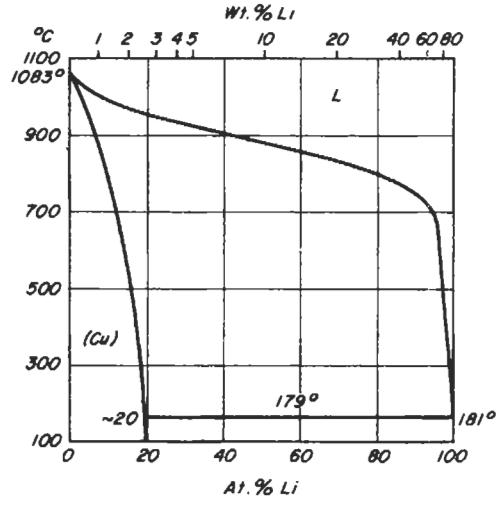
Cu–Ir


Wt % Ir
°C
2700
2300
1900
1500
1100
700
0
20
40
60
80
100
At % Ir
Liquid
2410°
1138 ± 5°
1083°
~4
~8
~3
1200
1100
1000
L
Cu
5
10

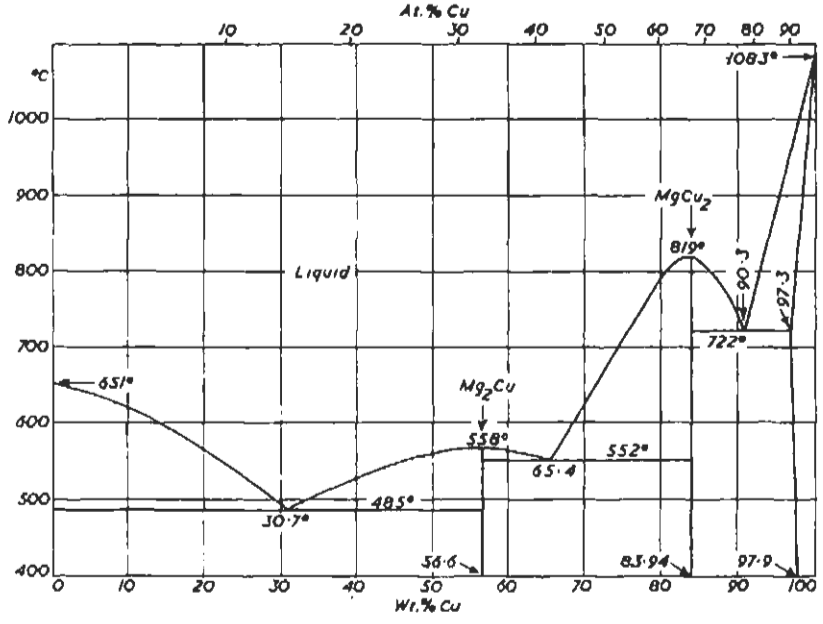
Cu–La


°C
Wt % La
Cu 10 20 30 40 50 60 70 80 90 La
1200
1000
800
600
400
200
0
1084.87°C
Cu6La
Cu2La
CuLa
865°C
905°C
9
805°C
830°C
745°C
24.5
525°C
Liquid
918°C
(γLa)
865°C
475°C
71
(βLa)
310°C
Cu5La
(Cu)
(αLa)
0 10 20 30 40 50 60 70 80 90 100
At % La

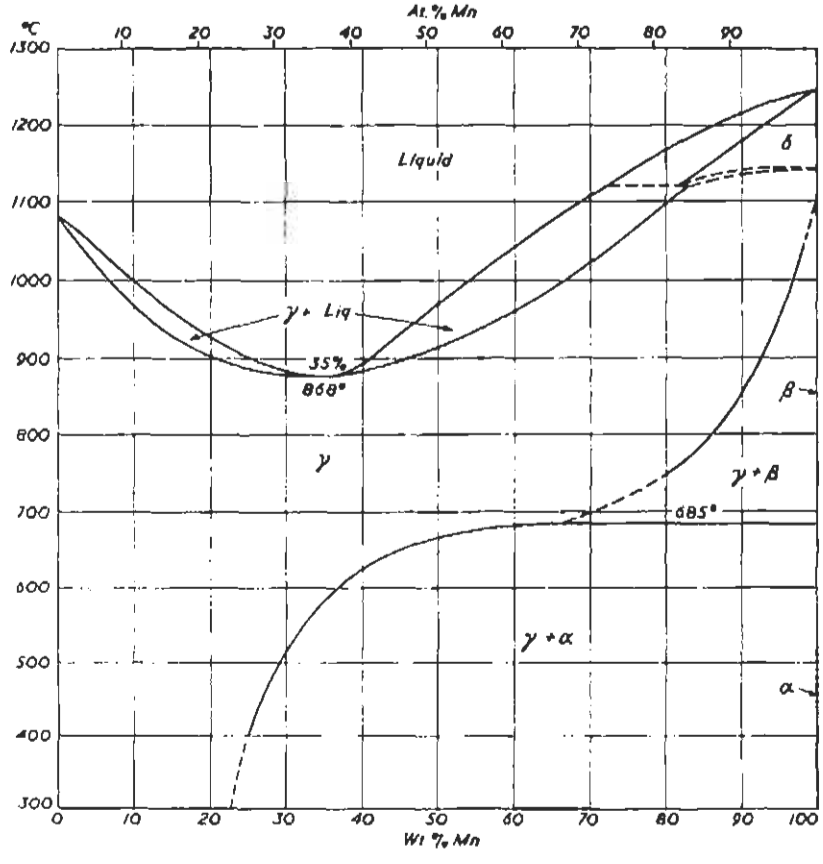
Cu–Li


Wt. % Li
°C
1 2 3 4 5 10 20 40 60 80
1100
1083°
900
700
500
300
100
L
(Cu)
~20
179°
181°
0 20 40 60 80 100
At. % Li

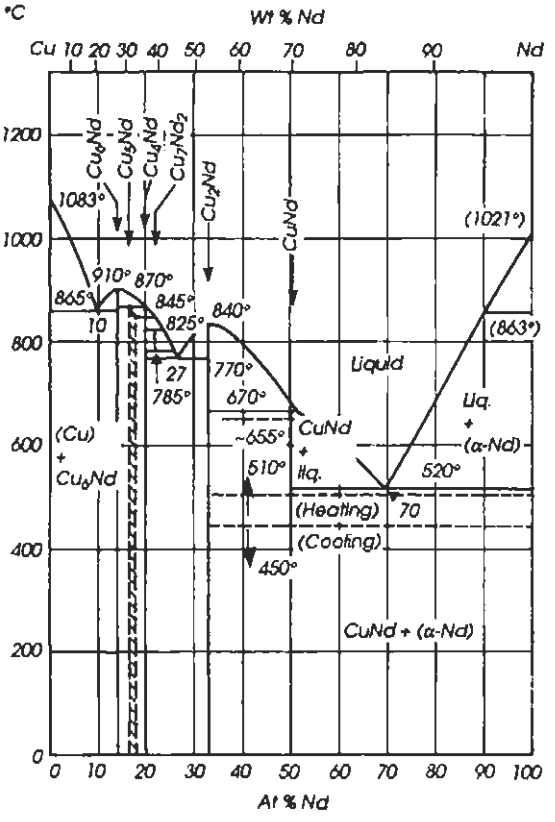
Cu–Mg


At.% Cu
10 20 30 40 50 60 70 80 90
°C
1000 900 800 700 600 500 400
1083°
MgCu2
819°
90·3
97·3
722°
Liquid
651°
Mg2Cu
558°
552°
65·4
485°
30·7°
56·6
83·94
97·9
0 10 20 30 40 50 60 70 80 90 100
Wt.% Cu

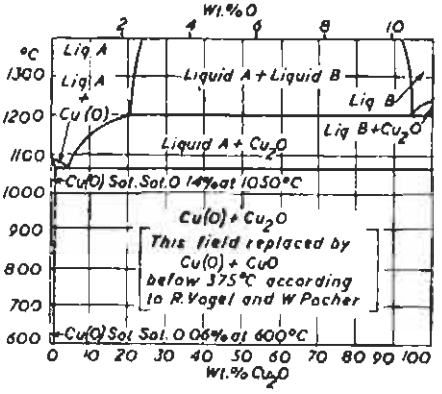
Cu–Mn


At.% Mn
°C
10 20 30 40 50 60 70 80 90
1300 1200 1100 1000 900 800 700 600 500 400 300
Liquid
δ
γ + Liq
35%
868°
γ
β
γ + β
685°
γ + α
α
0 10 20 30 40 50 60 70 80 90 100
Wt % Mn

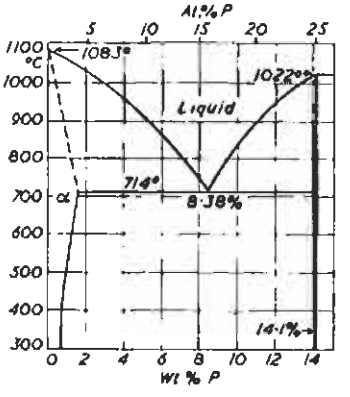
Cu–Nd


°C
Wt % Nd
Cu 10 20 30 40 50 60 70 80 90 Nd
1200
1000
800
600
400
200
0
0 10 20 30 40 50 60 70 80 90 100
At % Nd
Cu6Nd
Cu5Nd
Cu4Nd
Cu3Nd2
Cu2Nd
CuNd
1083°
910°
870°
865°
845°
825°
840°
10
27
785°
770°
670°
~655°
510°
450°
(1021°)
(863°)
520°
70
Liquid
Liq. + (α-Nd)
(Cu) + Cu6Nd
CuNd + liq.
(Heating)
(Cooling)
CuNd + (α-Nd)

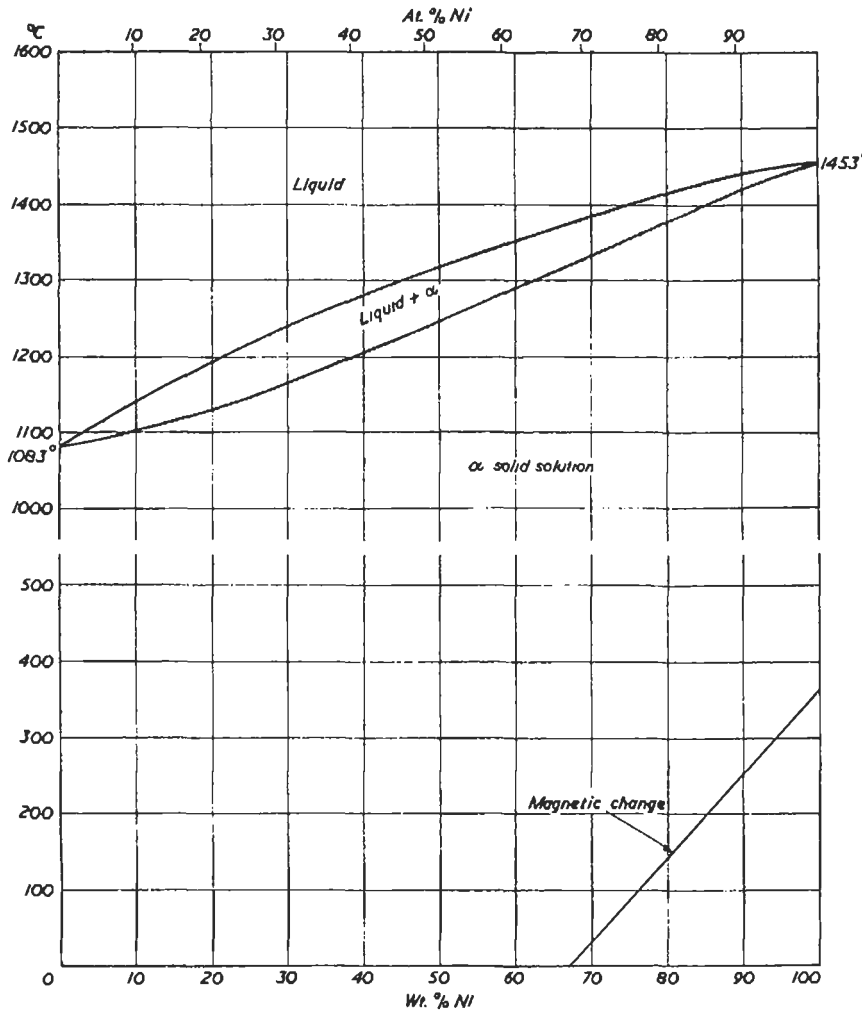
Cu–O


Wt.% O
2 4 6 8 10
°C
1300
1200
1100
1000
900
800
700
600
Liq A
Liq A + Cu(O)
Liquid A + Liquid B
Liq B
Liq B + Cu2O
Liquid A + Cu2O
Cu(O) Sat. Sat. O 1.4% at 1050°C
Cu(O) + Cu2O
This field replaced by Cu(O) + CuO below 375°C according to R. Vogel and W. Pocher
Cu(O) Sat. Sat. O 0.06% at 600°C
0 10 20 30 40 50 60 70 80 90 100
Wt.% Cu2O

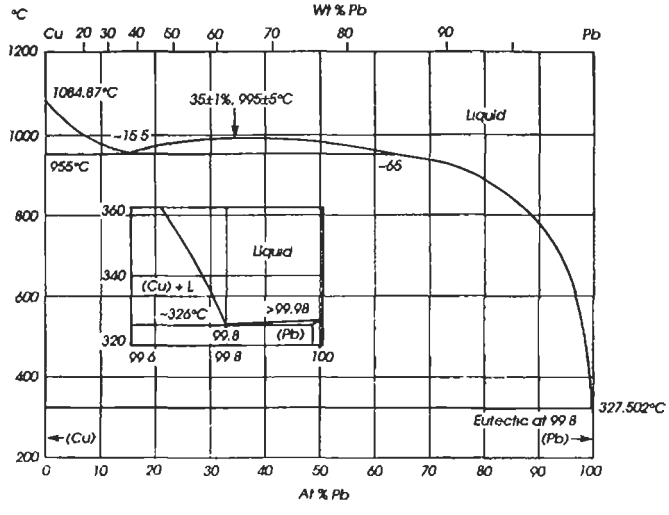
Cu–P


At.% P
5 10 15 20 25
1100
°C
1000
900
800
700
600
500
400
300
1083°
1022°
Liquid
714°
α
8·38%
14·1%
0 2 4 6 8 10 12 14
Wt % P

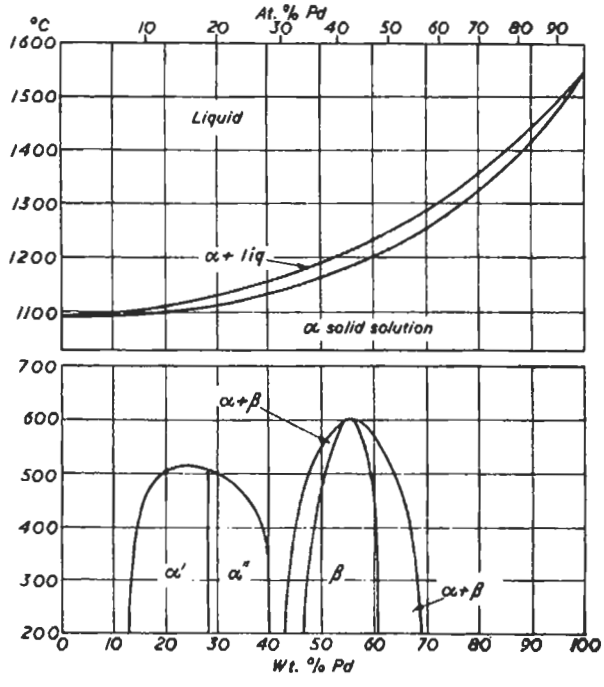
Cu–Ni


°C
At. % Ni
10 20 30 40 50 60 70 80 90
1600
1500
1400
1300
1200
1100
1083°
1000
Liquid
Liquid + α
1453°
α solid solution
500
400
300
200
100
0
Magnetic change
10 20 30 40 50 60 70 80 90 100
Wt. % Ni

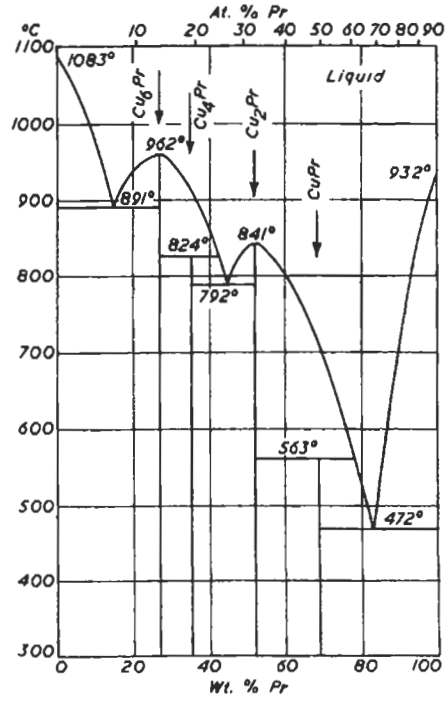
Cu–Pb


°C
Wt % Pb
Cu 20 30 40 50 60 70 80 90 Pb
1200
1084.87°C
35±1%, 995±5°C
Liquid
1000
~16.5
955°C
~66
800
360
Liquid
340
(Cu) + L
~326°C
>99.98
320
99.8
(Pb)
99.6
99.8
100
600
400
327.502°C
Eutectic at 99.8
(Cu)
(Pb)
200
0 10 20 30 40 50 60 70 80 90 100
At % Pb

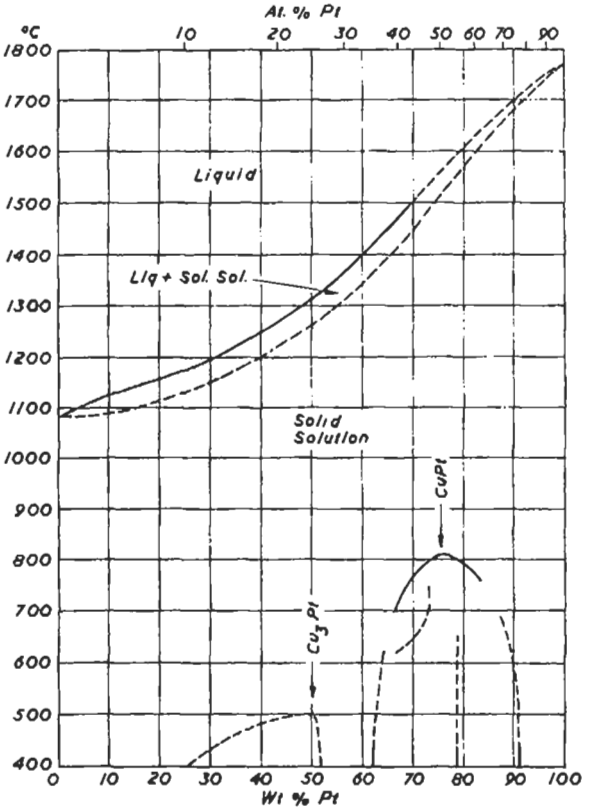
Cu–Pd


°C
At. % Pd
10 20 30 40 50 60 70 80 90
1600
1500
1400
1300
1200
1100
Liquid
α + liq
α solid solution
700
600
500
400
300
200
α+β
α'
α''
β
α+β
0 10 20 30 40 50 60 70 80 90 100
Wt. % Pd

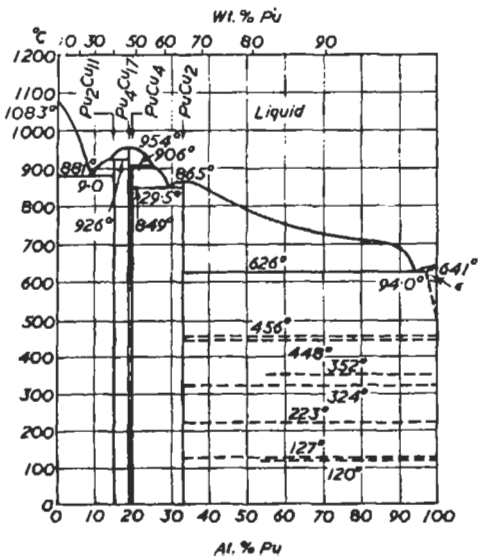
Cu–Pr


°C
At. % Pr
10 20 30 40 50 60 70 80 90
1100
1000
900
800
700
600
500
400
300
1083°
Cu8Pr
Cu4Pr
Cu2Pr
CuPr
Liquid
962°
932°
891°
824°
841°
792°
563°
472°
0 20 40 60 80 100
Wt. % Pr

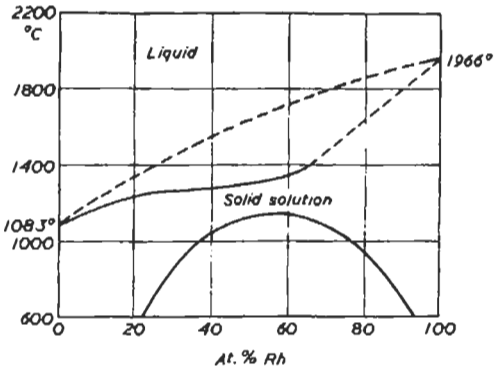
Cu–Pt


At. % Pt
°C
10 20 30 40 50 60 70 90
1800 1700 1600 1500 1400 1300 1200 1100 1000 900 800 700 600 500 400
Liquid
Liq + Sol. Sol.
Solid Solution
CuPt
Cu3Pt
0 10 20 30 40 50 60 70 80 90 100
Wt % Pt

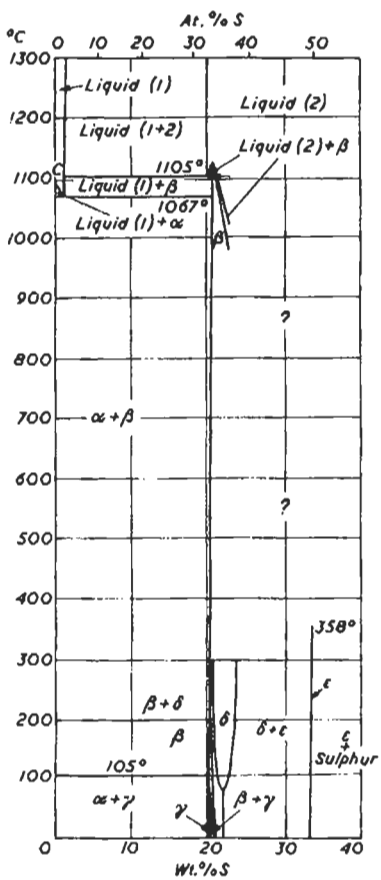
Cu–Pu


Wt. % Pu
°C
10 30 50 60 70 80 90
1200 1100 1083° 1000 900 800 700 600 500 400 300 200 100 0
Pu2Cu11
Pu4Cu17
PuCu4
PuCu2
Liquid
954°
906°
881°
9·0
865°
829·5°
926°
849°
626°
641°
94·0°
456°
448°
352°
324°
223°
127°
120°
0 10 20 30 40 50 60 70 80 90 100
At. % Pu

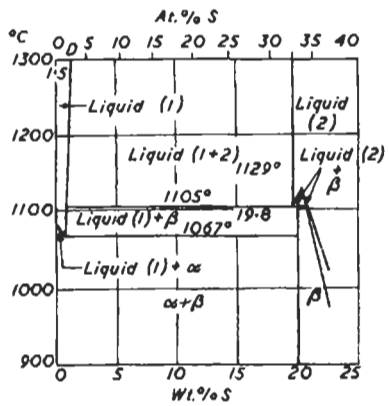
Cu–Rh



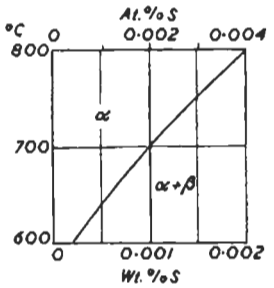
Cu–S



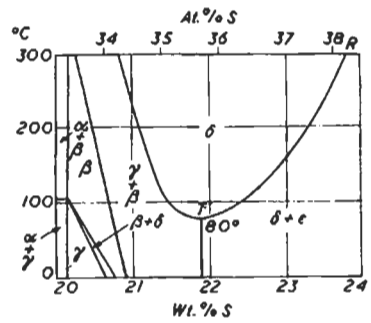
Cu–S



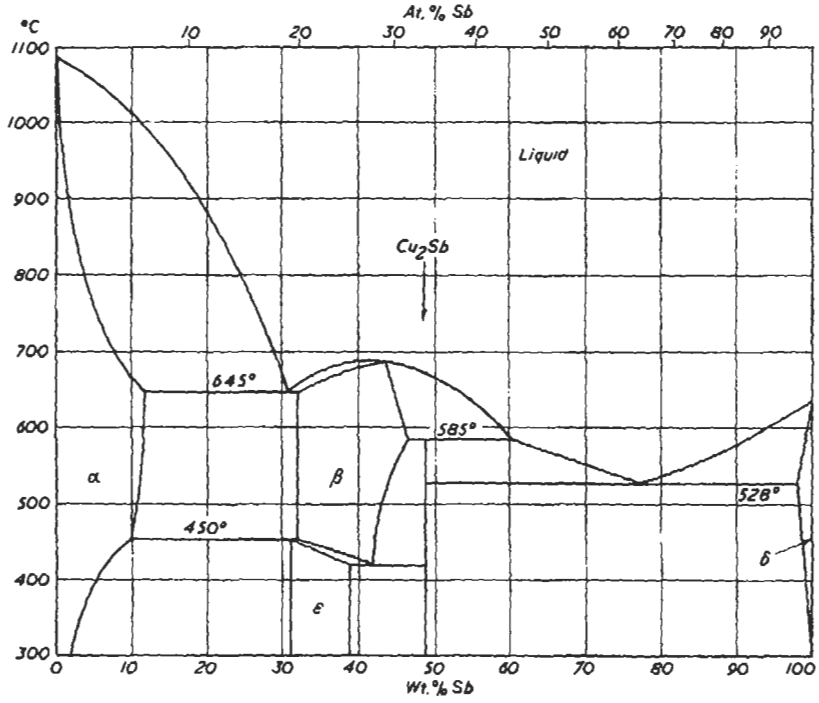
Cu–S



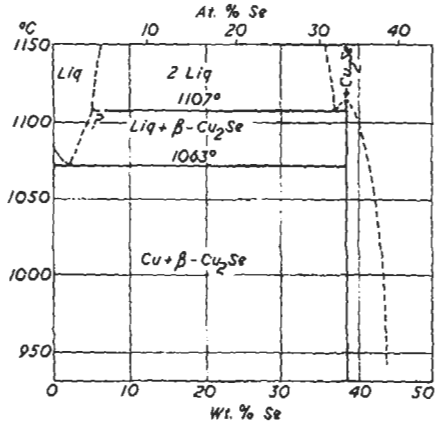
Cu–S



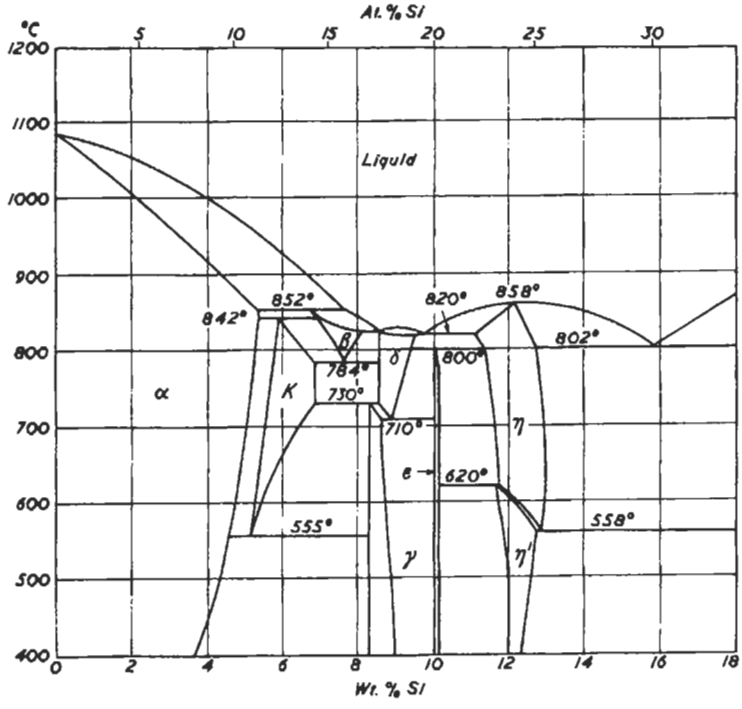
Cu–Sb


°C
At. % Sb
Liquid
Cu_2Sb
645°
585°
528°
450°
α
β
ε
δ
Wt. % Sb

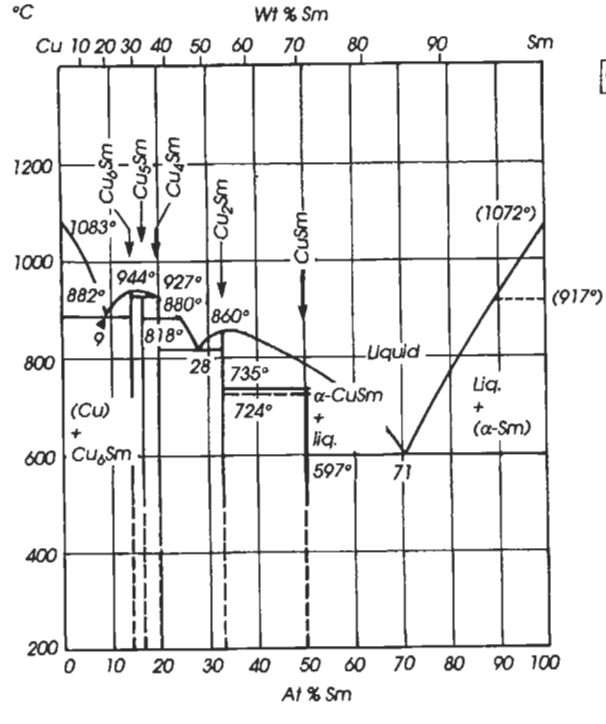
Cu–Se


°C
At. % Se
Liq
2 Liq
1107°
Liq + β - Cu_2Se
1063°
Cu + β - Cu_2Se
Cu_2Se
Wt. % Se

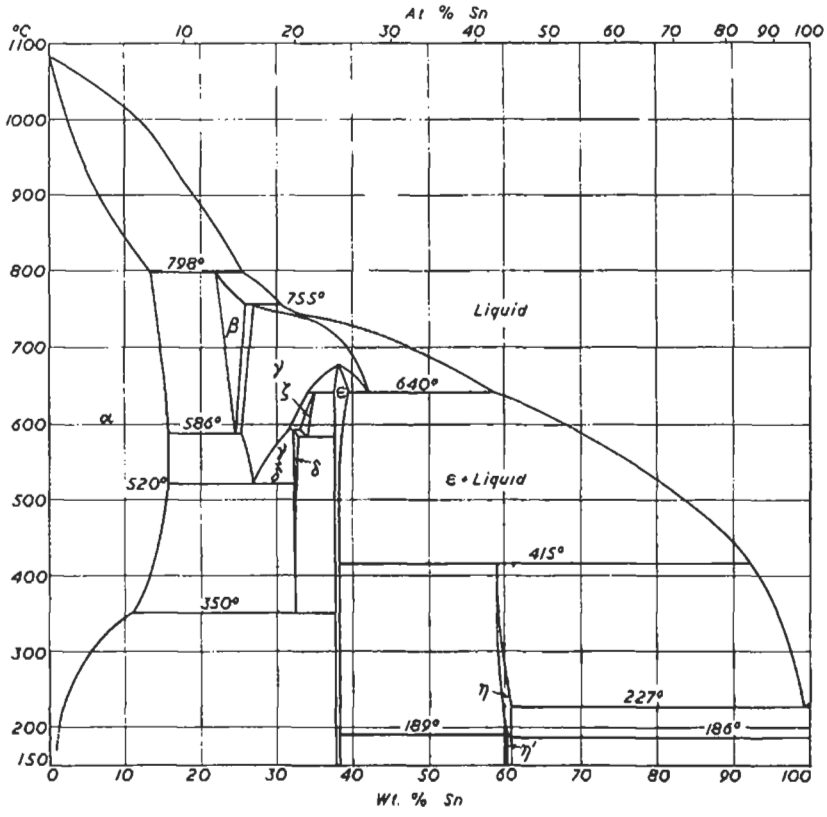
Cu–Si


°C
At. % Si
5
10
15
20
25
30
1200
1100
1000
900
800
700
600
500
400
Liquid
842°
852°
820°
858°
802°
784°
730°
710°
800°
620°
555°
558°
α
K
β
δ
η
η'
ε
γ
0
2
4
6
8
10
12
14
16
18
Wt. % Si

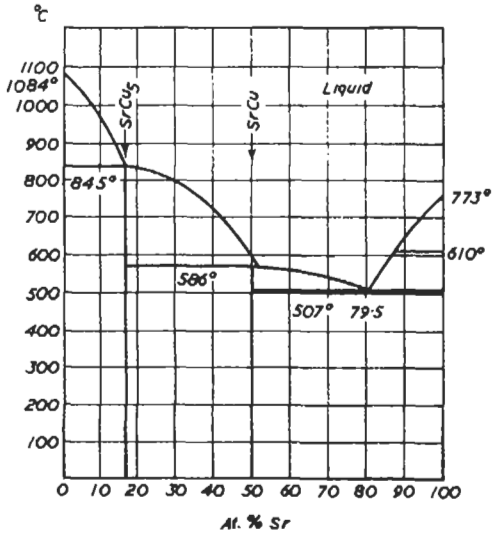
Cu–Sm


°C
Wt % Sm
Cu 10 20 30 40 50 60 70 80 90 Sm
Cu6Sm
Cu5Sm
Cu4Sm
Cu2Sm
CuSm
1200
1000
800
600
400
200
1083°
882°
944°
927°
880°
860°
818°
9
28
735°
724°
597°
71
(1072°)
(917°)
Liquid
(Cu)
+
Cu6Sm
α-CuSm
+
liq.
Liq.
+
(α-Sm)
0 10 20 30 40 50 60 70 80 90 100
At % Sm

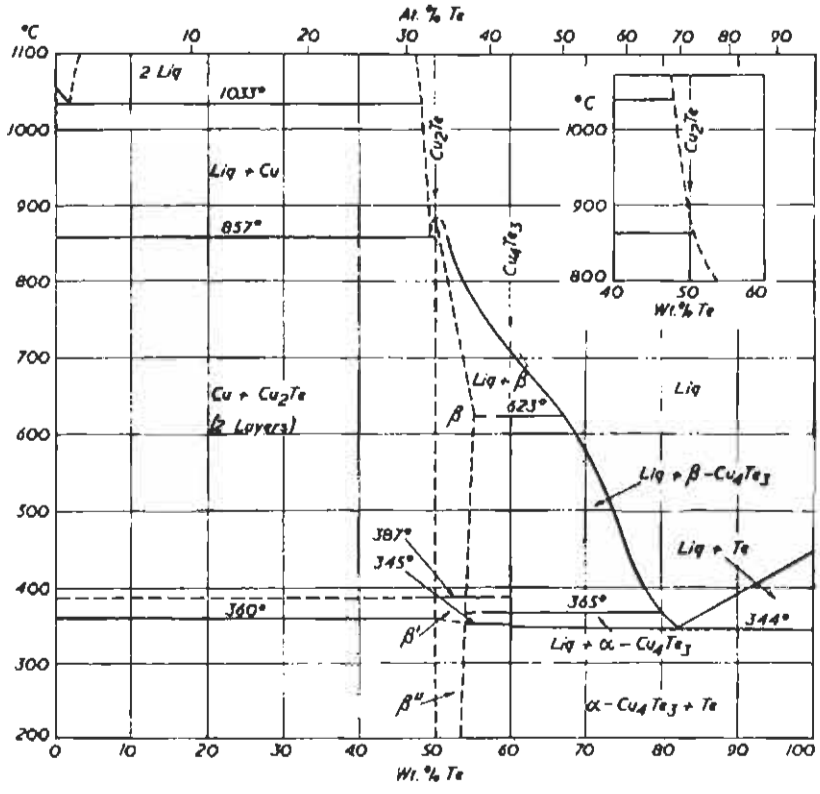
Cu–Sn


At % Sn
°C
10 20 30 40 50 60 70 80 90 100
1100
1000
900
800
700
600
500
400
300
200
150
798°
755°
Liquid
640°
586°
520°
415°
350°
227°
189°
186°
ε + Liquid
α
β
γ
ζ
δ
ε
η
η'
0 10 20 30 40 50 60 70 80 90 100
Wt. % Sn

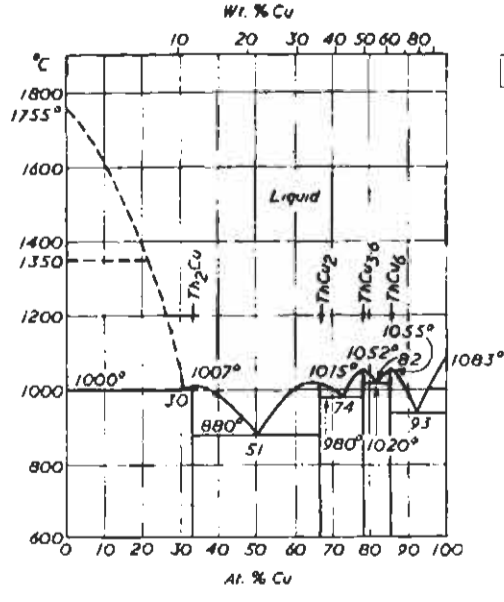
Cu–Sr


°C
1100
1084°
1000
900
800
700
600
500
400
300
200
100
SrCu5
SrCu
Liquid
845°
773°
610°
586°
507°
79·5
0 10 20 30 40 50 60 70 80 90 100
At. % Sr

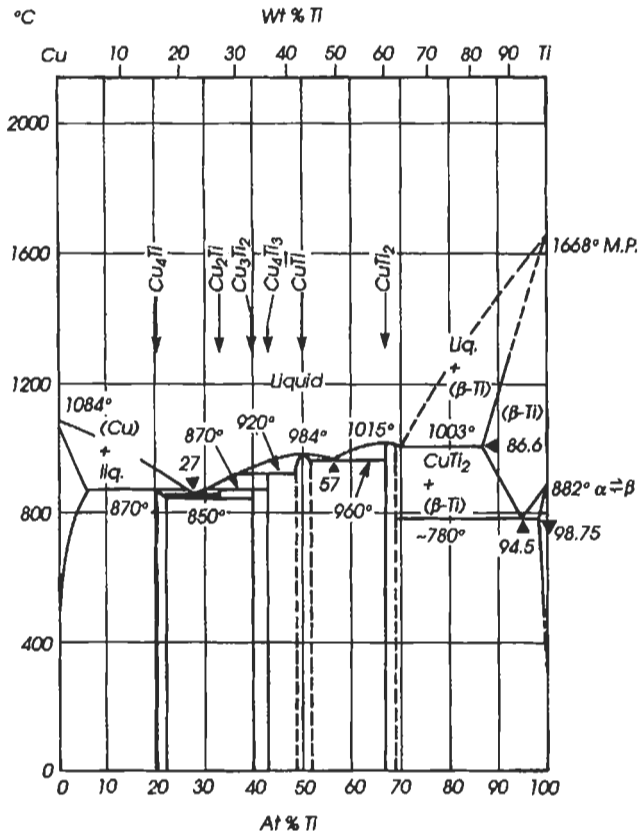
Cu–Te


At. % Te
°C
2 Liq
1033°
Liq + Cu
857°
Cu + Cu2Te
(2 Layers)
Cu2Te
Cu4Te3
Liq + β
623°
β
Liq
Liq + β – Cu4Te3
387°
345°
360°
β'
β''
365°
344°
Liq + Te
Liq + α – Cu4Te3
α – Cu4Te3 + Te
Wt. % Te

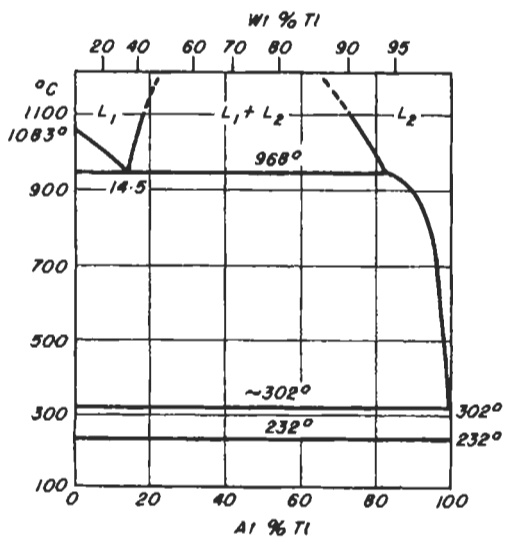
Cu–Th


Wt. % Cu
°C
1755°
Liquid
Th2Cu
ThCu2
ThCu3.6
ThCu6
1055°
1052°
1083°
1015°
1007°
1000°
880°
980°
1020°
30
51
74
82
93
At. % Cu

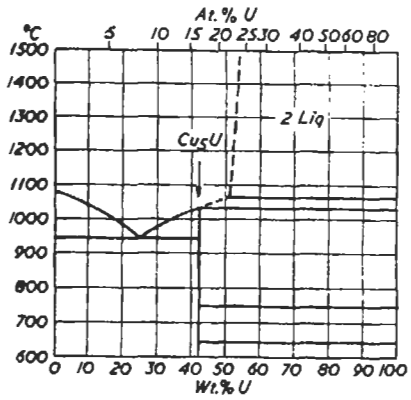
Cu–Ti


°C
Wt % Ti
Cu 10 20 30 40 50 60 70 80 90 Ti
2000
1600
1200
800
400
0
Cu4Ti
Cu2Ti
Cu3Ti2
Cu4Ti3
CuTi
CuTi2
1668° M.P.
Liq. + (β-Ti)
Liquid
1084° (Cu) + liq.
870°
920°
984°
1015°
1003°
(β-Ti)
86.6
27
57
CuTi2 + (β-Ti)
882° α⇌β
870°
850°
960°
~780°
94.5
98.75
0 10 20 30 40 50 60 70 80 90 100
At % Ti

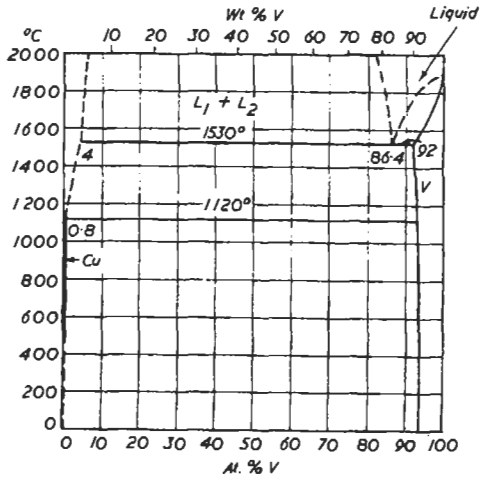
Cu–Tl


Wt % Tl
20 40 60 70 80 90 95
°C
1100
1083°
L1
L1 + L2
L2
968°
14·5
900
700
500
~302°
300
232°
302°
232°
100
0 20 40 60 80 100
At % Tl

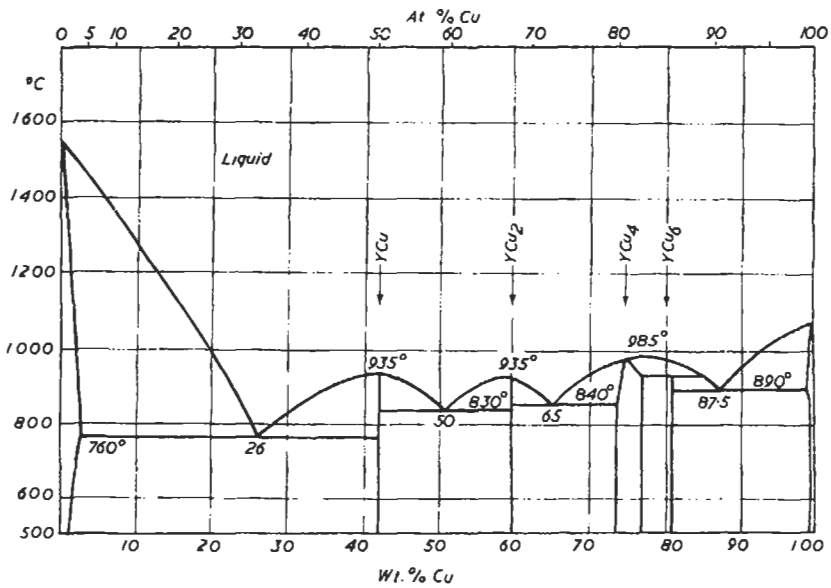
Cu–U


At. % U
°C
5 10 15 20 25 30 40 50 60 80
1500
1400
1300
1200
1100
1000
900
800
700
600
2 Liq
Cu5U
0 10 20 30 40 50 60 70 80 90 100
Wt. % U

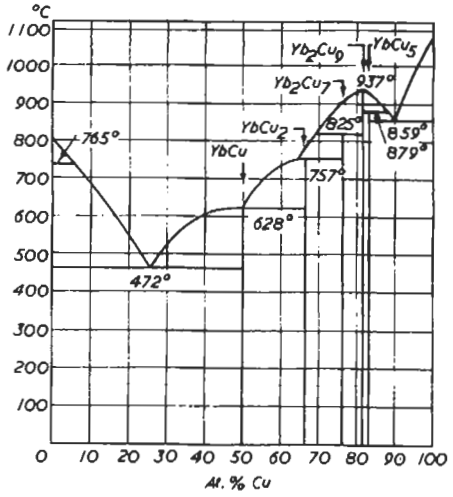
Cu–V


Wt % V
Liquid
°C
10 20 30 40 50 60 70 80 90
2000
1800
1600
1400
1200
1000
800
600
400
200
0
L1 + L2
1530°
1120°
14
86·4
92
V
0·8
Cu
0 10 20 30 40 50 60 70 80 90 100
At. % V

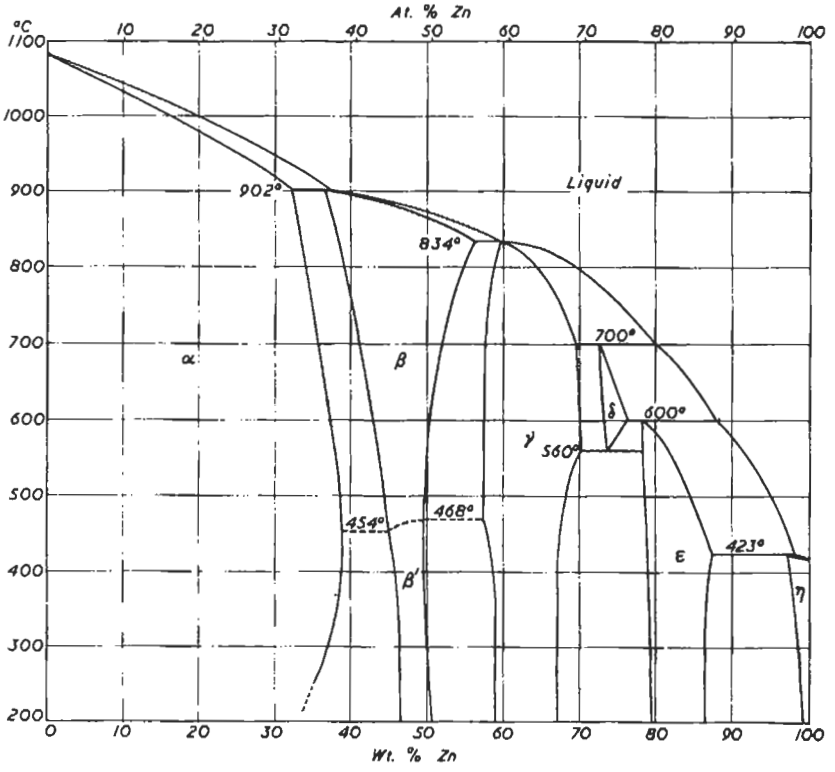
Cu–Y


At % Cu
0 5 10 20 30 40 50 60 70 80 90 100
°C
1600
1400
1200
1000
800
600
500
Liquid
YCu
YCu2
YCu4
YCu6
935°
935°
985°
890°
830°
840°
760°
26
50
65
87·5
10 20 30 40 50 60 70 80 90 100
Wt. % Cu

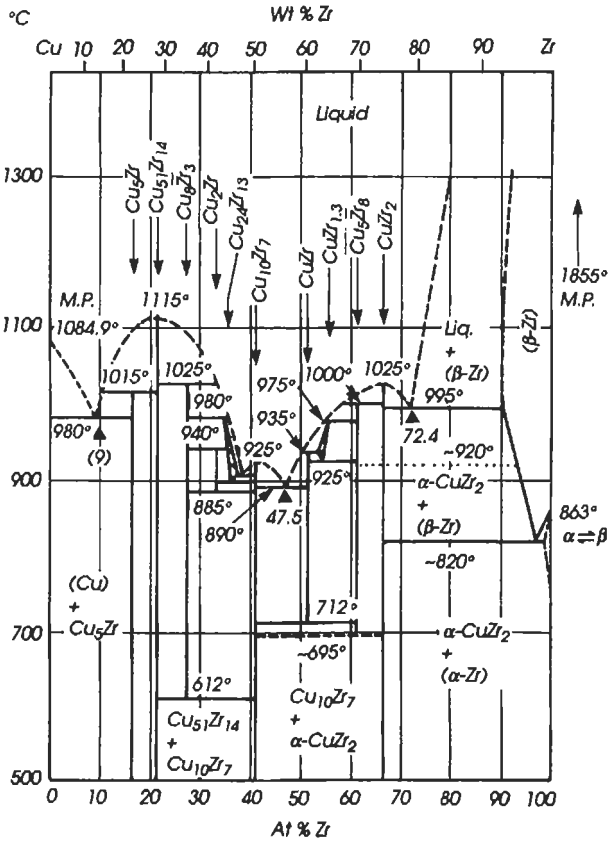
Cu–Yb


°C
1100
1000
900
800
700
600
500
400
300
200
100
0 10 20 30 40 50 60 70 80 90 100
At. % Cu
Yb_2Cu_9
$YbCu_5$
Yb_2Cu_7
937°
$YbCu_2$
825°
859°
879°
765°
YbCu
757°
628°
472°

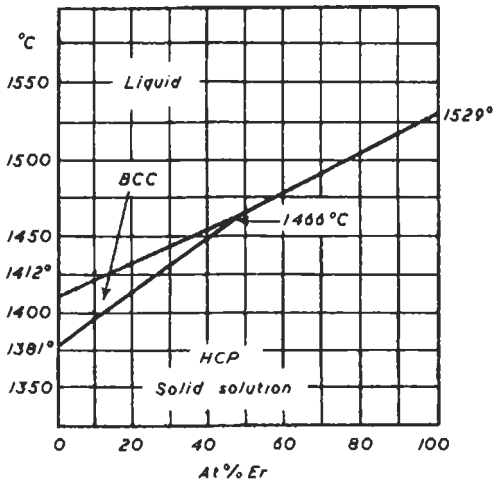
Cu–Zn


At. % Zn
°C
1100
1000
900
800
700
600
500
400
300
200
10 20 30 40 50 60 70 80 90 100
0 10 20 30 40 50 60 70 80 90 100
Wt. % Zn
902°
Liquid
834°
700°
α
β
δ
600°
γ
560°
454°
468°
β′
ε
423°
η

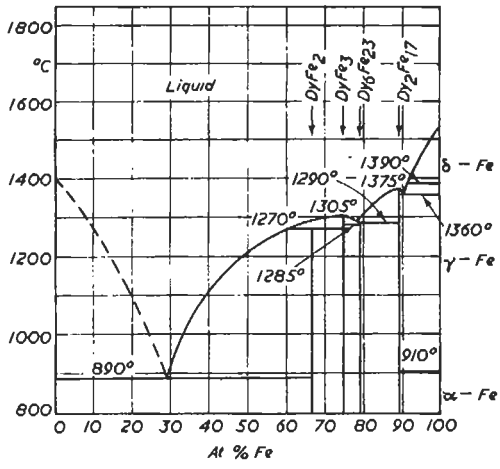
Cu–Zr


°C
Wt % Zr
Cu 10 20 30 40 50 60 70 80 90 Zr
Liquid
1300
1100
900
700
500
Cu_9Zr
$Cu_{51}Zr_{14}$
Cu_8Zr_3
Cu_2Zr
$Cu_{24}Zr_{13}$
$Cu_{10}Zr_7$
CuZr
$CuZr_{1.3}$
Cu_5Zr_8
$CuZr_2$
M.P.
1084.9°
1115°
1855°
M.P.
(β-Zr)
Liq.
+
(β-Zr)
1015°
1025°
980°
940°
925°
975°
935°
1000°
1025°
995°
72.4
~920°
980°
(9)
885°
890°
47.5
925°
α-$CuZr_2$
+
(β-Zr)
863°
α⇌β
~820°
(Cu)
+
Cu_5Zr
712°
~695°
α-$CuZr_2$
+
(α-Zr)
612°
$Cu_{51}Zr_{14}$
+
$Cu_{10}Zr_7$
$Cu_{10}Zr_7$
+
α-$CuZr_2$
0 10 20 30 40 50 60 70 80 90 100
At % Zr

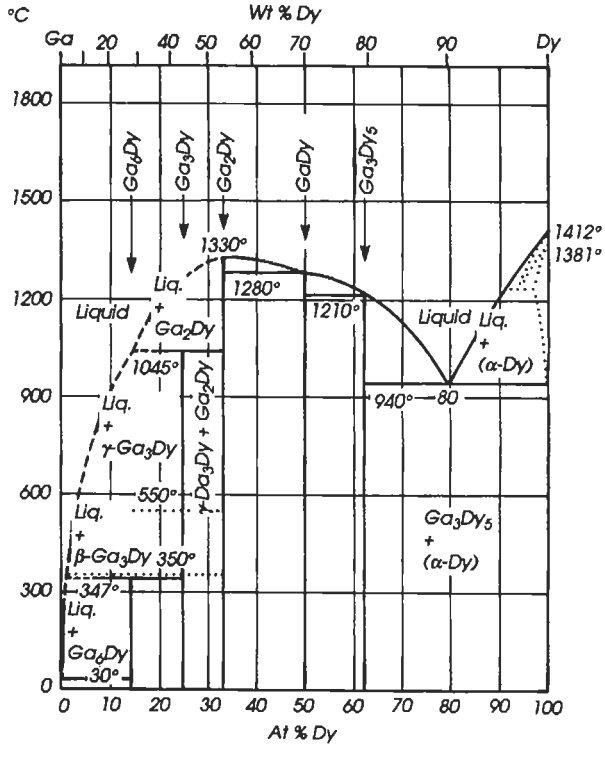
Dy–Er


°C
1550
1500
1450
1412°
1400
1381°
1350
Liquid
1529°
BCC
1466 °C
HCP
Solid solution
0 20 40 60 80 100
At % Er

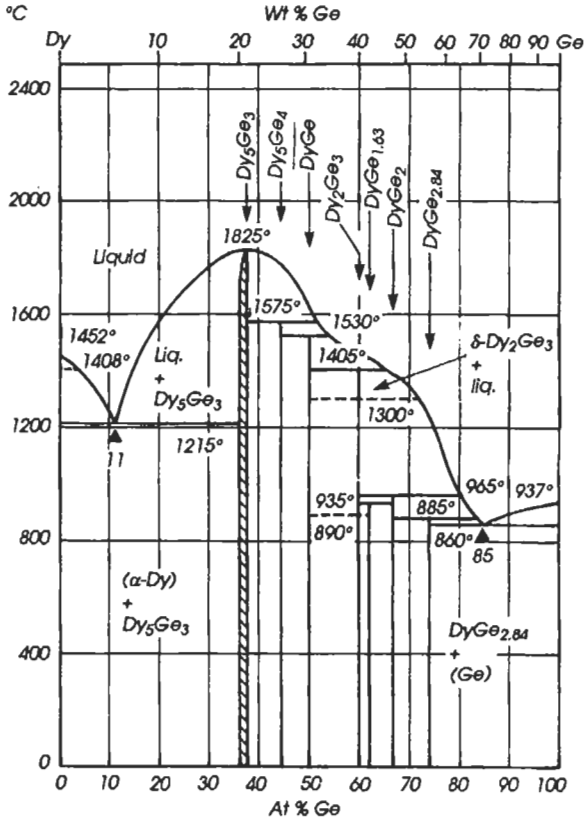
Dy–Fe


°C
Liquid
Dy_2Fe_{17}
Dy_6Fe_{23}
$DyFe_3$
$DyFe_2$
1390°
1375°
1290°
1305°
1270°
1285°
1360°
910°
890°
δ – Fe
γ – Fe
α – Fe
At % Fe

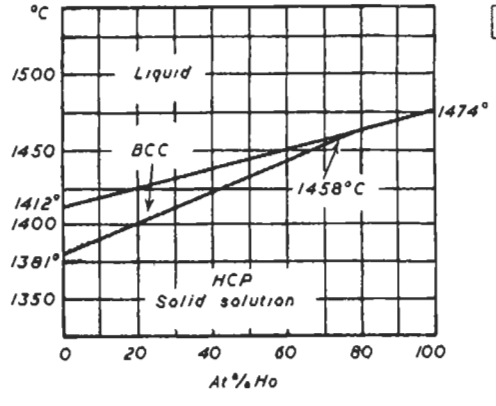
Dy–Ga


°C
Wt % Dy
Ga
Dy
Ga_6Dy
Ga_3Dy
Ga_2Dy
GaDy
Ga_3Dy_5
1330°
1280°
1210°
1412°
1381°
Liquid
Liq. + Ga_2Dy
1045°
Liq. + γ-Ga_3Dy
550°
Liq. + β-Ga_3Dy
350°
347°
Liq. + Ga_6Dy
30°
γ-Ga_3Dy + Ga_2Dy
Liquid
Liq. + (α-Dy)
940°
80
Ga_3Dy_5 + (α-Dy)
At % Dy

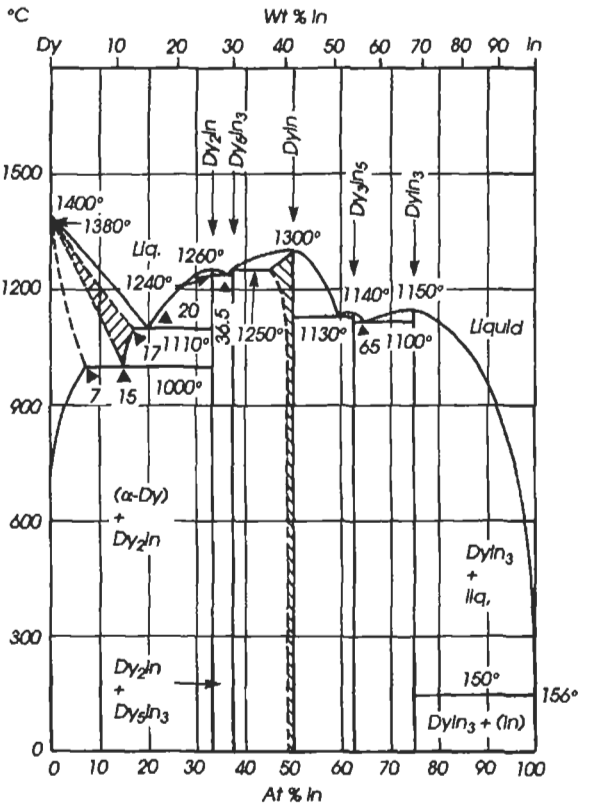
Dy–Ge


°C
Wt % Ge
Dy
10
20
30
40
50
60
70
80
90
Ge
2400
2000
1600
1200
800
400
0
Dy_5Ge_3
Dy_5Ge_4
DyGe
Dy_2Ge_3
$DyGe_{1.63}$
$DyGe_2$
$DyGe_{2.84}$
Liquid
1825°
1575°
1530°
1452°
1408°
Liq.
+
Dy_5Ge_3
1405°
δ-Dy_2Ge_3
+
liq.
1300°
11
1215°
965°
937°
935°
885°
890°
860°
85
(α-Dy)
+
Dy_5Ge_3
$DyGe_{2.84}$
+
(Ge)
0
10
20
30
40
50
60
70
80
90
100
At % Ge

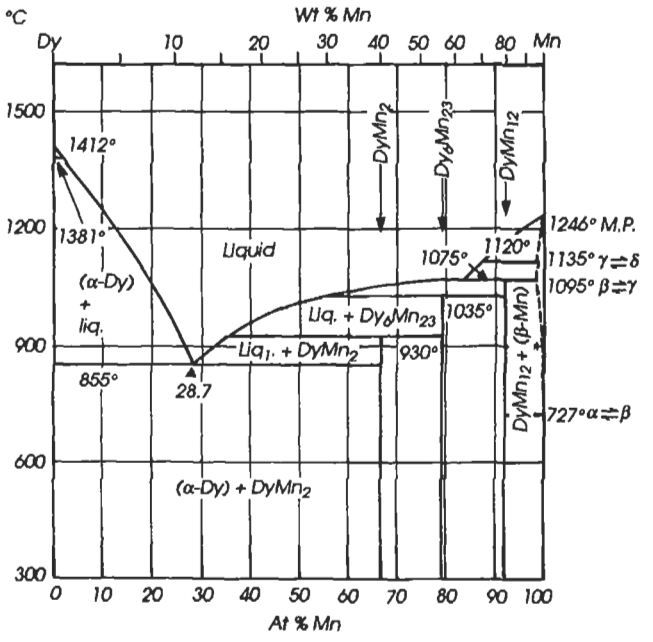
Dy–Ho


°C
1500
1450
1412°
1400
1381°
1350
Liquid
BCC
HCP
Solid solution
1474°
1458°C
0
20
40
60
80
100
At % Ho

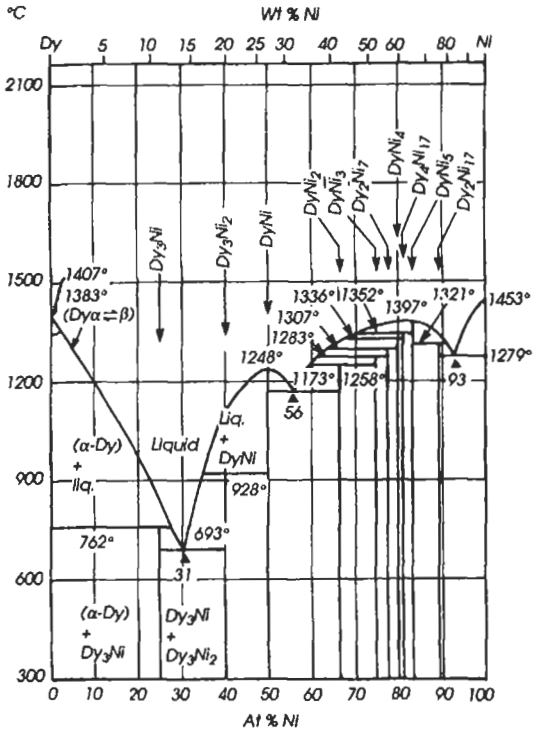
Dy–In


°C
Wt % In
Dy
In
Dy_2In
Dy_5In_3
DyIn
Dy_3In_5
$DyIn_3$
1400°
1380°
Liq.
1260°
1240°
1300°
1140°
1150°
Liquid
1110°
1250°
1130°
1100°
1000°
(α-Dy) + Dy_2In
$DyIn_3$ + liq.
Dy_2In + Dy_5In_3
150°
156°
$DyIn_3$ + (In)
At % In

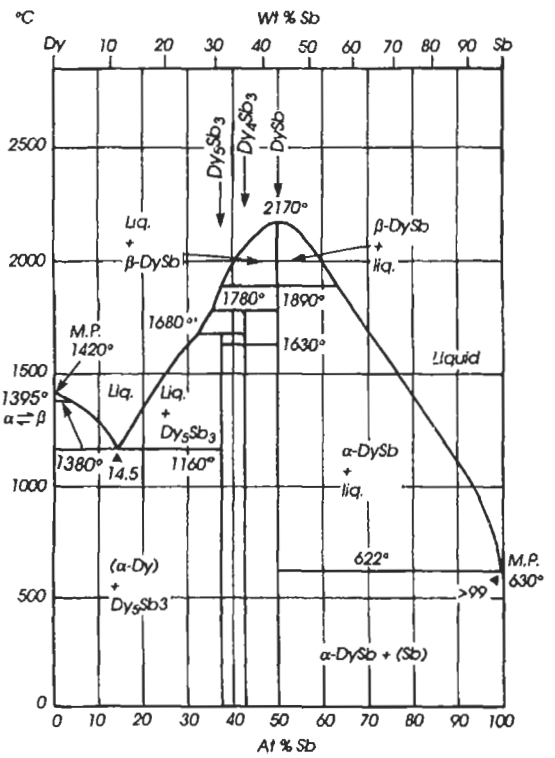
Dy–Mn


°C
Wt % Mn
Dy
Mn
$DyMn_2$
Dy_6Mn_{23}
$DyMn_{12}$
1412°
1381°
Liquid
1246° M.P.
1120°
1075°
1135° γ ⇌ δ
1095° β ⇌ γ
(α-Dy) + liq.
Liq. + Dy_6Mn_{23}
1035°
Liq_1. + $DyMn_2$
930°
855°
28.7
$DyMn_{12}$ + (β-Mn)
727° α ⇌ β
(α-Dy) + $DyMn_2$
At % Mn

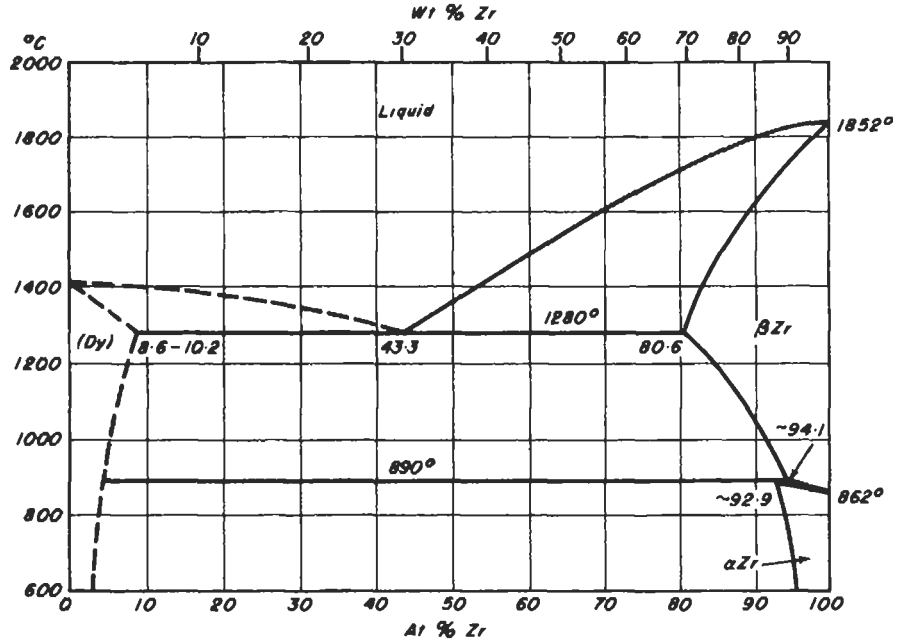
Dy–Ni


°C
Wt % Ni
Dy
Ni
At % Ni
Dy3Ni
Dy3Ni2
DyNi
DyNi2
DyNi3
Dy2Ni7
DyNi4
Dy4Ni17
DyNi5
Dy2Ni17
1407°
1383°
(Dyα⇄β)
1336°
1352°
1307°
1397°
1321°
1453°
1283°
1279°
1248°
1173°
1258°
93
56
Liq.
+
DyNi
(α-Dy)
+
liq.
Liquid
928°
762°
693°
31
(α-Dy)
+
Dy3Ni
Dy3Ni
+
Dy3Ni2

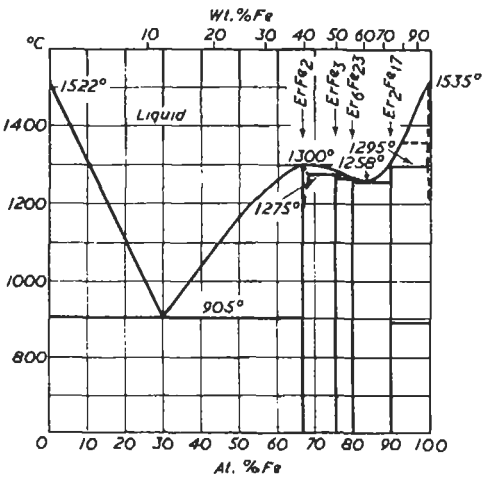
Dy–Sb


°C
Wt % Sb
Dy
Sb
At % Sb
Dy5Sb3
Dy4Sb3
DySb
2170°
Liq.
+
β-DySb
β-DySb
+
liq.
1780°
1890°
1680°
M.P.
1420°
1630°
Liquid
1395°
α⇄β
Liq.
Liq.
+
Dy5Sb3
1380°
14.5
1160°
α-DySb
+
liq.
622°
M.P.
630°
(α-Dy)
+
Dy5Sb3
>99
α-DySb + (Sb)

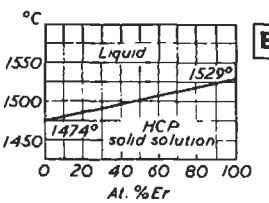
Dy–Zr



Er–Fe

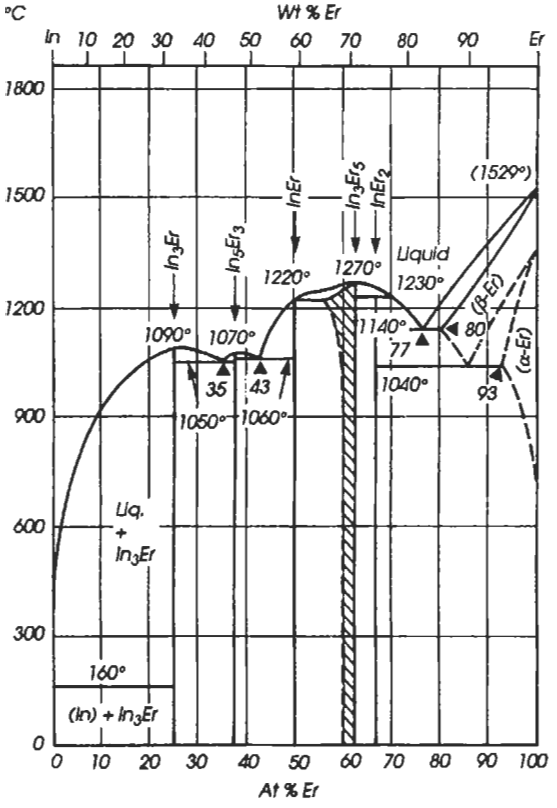


Er–Ho

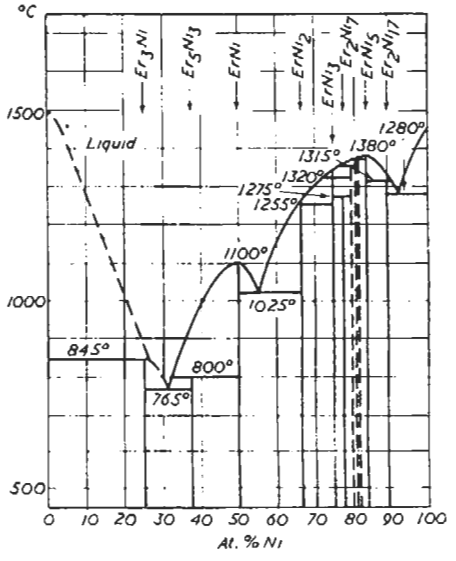


For other Dysprosion Diagrams see: Moffat, *Handbook of Binary Diagrams*, Genium Publication Corp., New York.

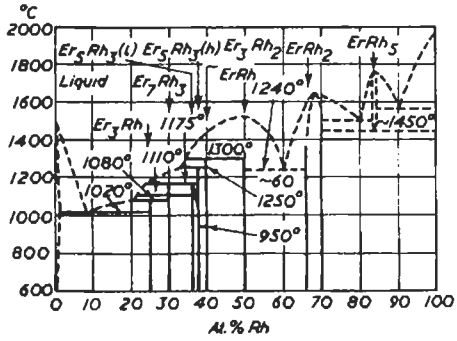
Er–In


°C
Wt % Er
In 10 20 30 40 50 60 70 80 90 Er
1800
1500
1200
900
600
300
0
In_3Er
In_5Er_3
InEr
In_3Er_5
$InEr_2$
(1529°)
Liquid
1230°
1270°
1220°
1090°
1070°
1140°
80
77
1040°
93
35
43
1050°
1060°
(β-Er)
(α-Er)
Liq.
+
In_3Er
160°
(In) + In_3Er
0 10 20 30 40 50 60 70 80 90 100
At % Er

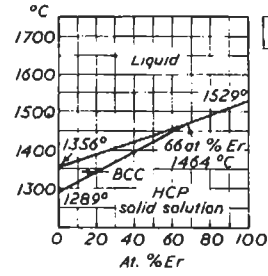
Er–Ni


°C
Er_3Ni
Er_5Ni_3
ErNi
$ErNi_2$
$ErNi_3$
Er_2Ni_7
$ErNi_5$
Er_2Ni_{17}
1500
1000
500
Liquid
1280°
1380°
1315°
1320°
1275°
1255°
1100°
1025°
845°
800°
765°
0 10 20 30 40 50 60 70 80 90 100
At. % Ni

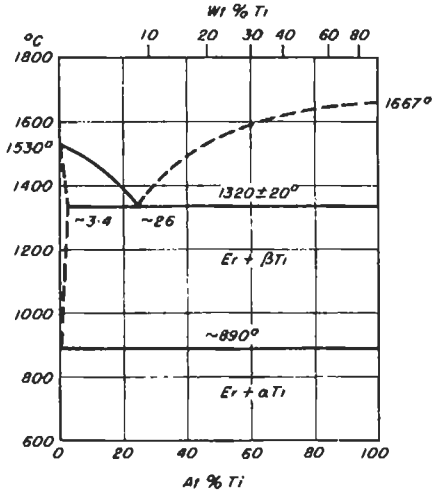
Er–Rh



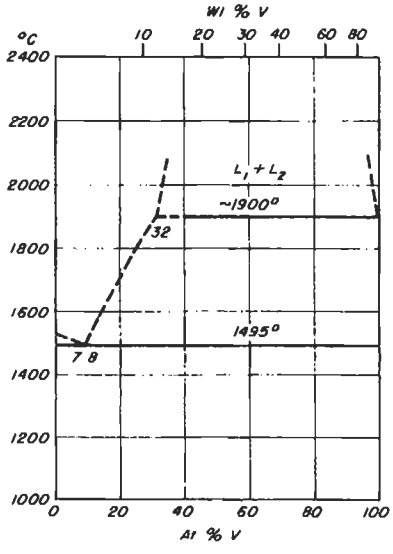
Er–Tb



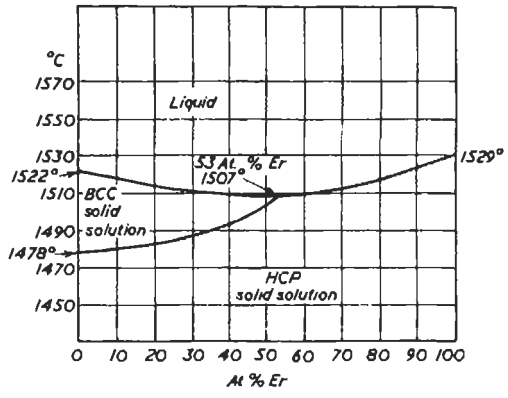
Er–Ti



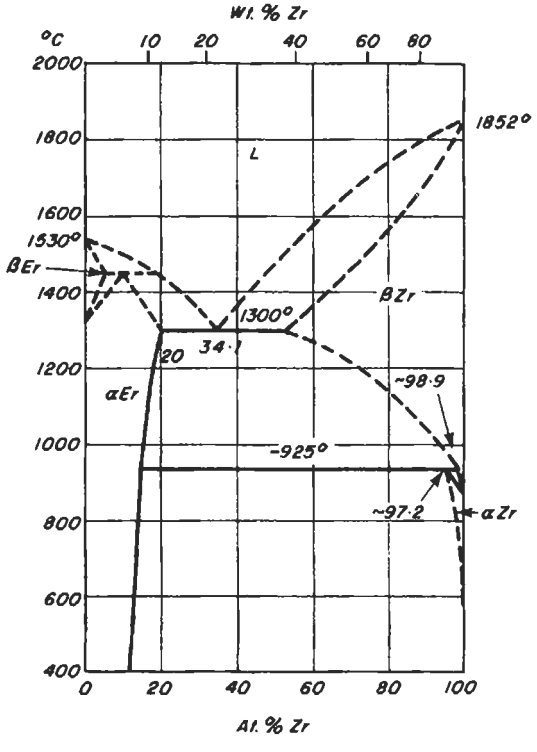
Er–V



Er–Y

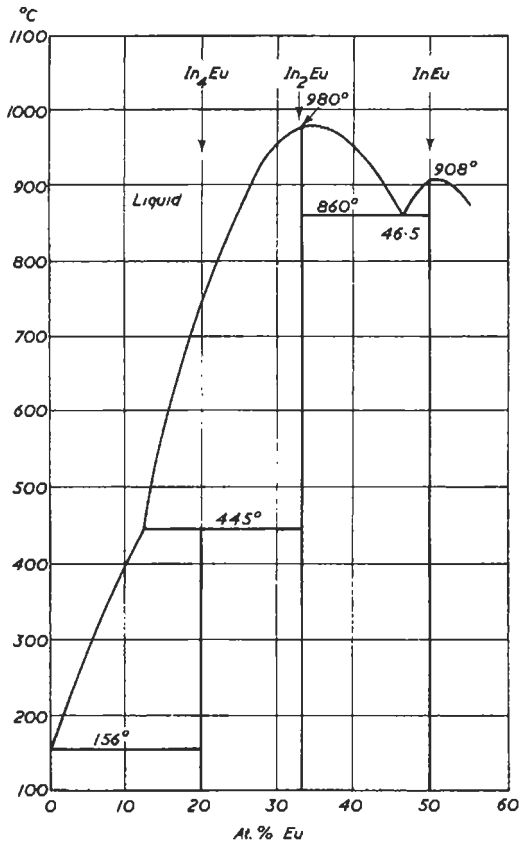


Er–Zr

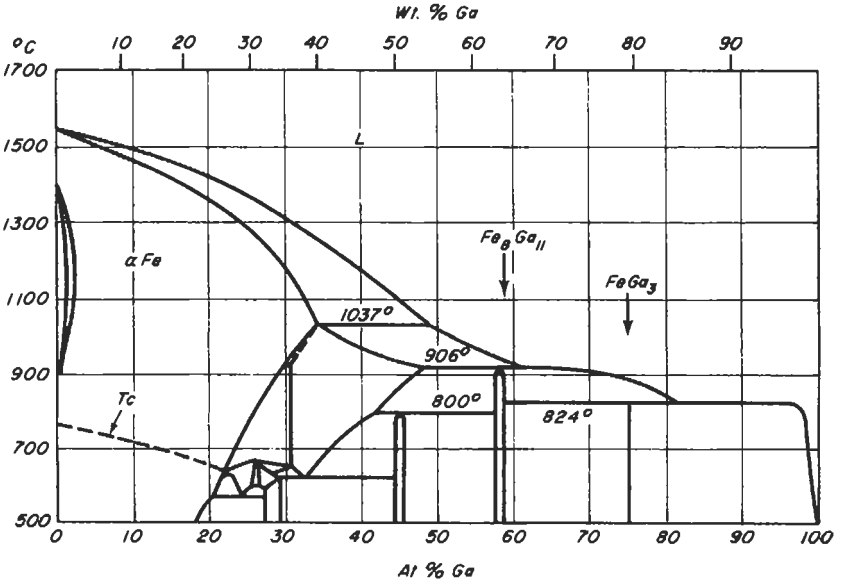


For other Erbium Diagrams see: Moffat, *Handbook of Binary Diagrams*, Genium Publication Corp., New York.

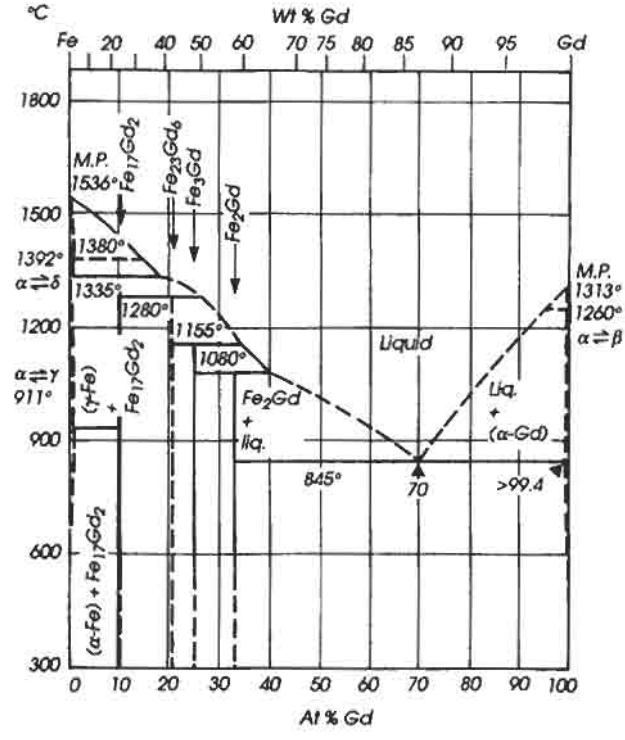
Eu–In


°C
1100
1000
900
800
700
600
500
400
300
200
100
In_4Eu
In_2Eu
InEu
980°
908°
Liquid
860°
46·5
445°
156°
0
10
20
30
40
50
60
At. % Eu

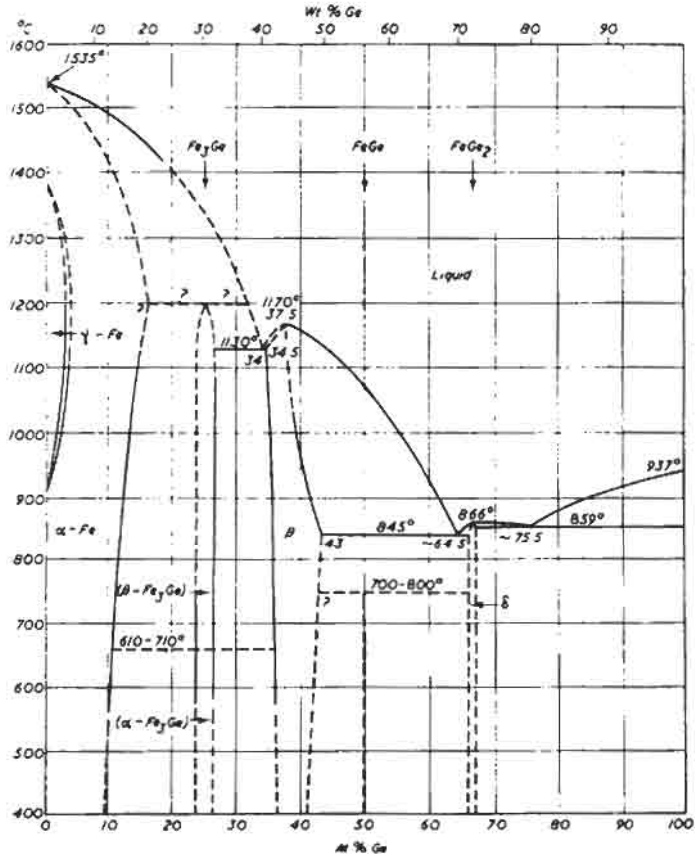
Fe–Ga


Wt. % Ga
°C
10
20
30
40
50
60
70
80
90
1700
1500
1300
1100
900
700
500
L
α Fe
Fe_3Ga_{11}
$FeGa_3$
1037°
906°
800°
824°
Tc
0
10
20
30
40
50
60
70
80
90
100
Al % Ga

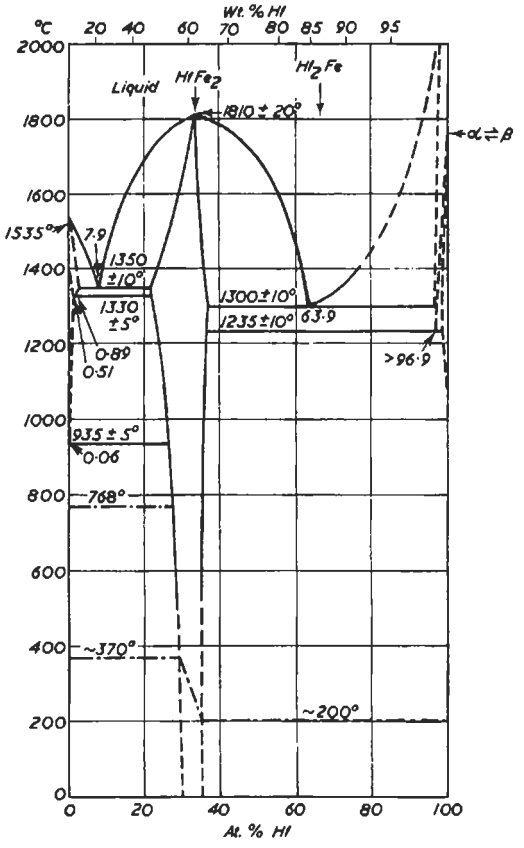
Fe–Gd


°C
Wt % Gd
Fe 20 40 50 60 70 75 80 85 90 95 Gd
1800
1500
1392°
α⇌δ
1380°
1335°
1280°
1200
1155°
1080°
α⇌γ
911°
900
600
300
M.P.
1536°
Fe17Gd2
Fe23Gd6
Fe3Gd
Fe2Gd
(γ-Fe)
+
Fe17Gd2
Fe2Gd
+
liq.
Liquid
M.P.
1313°
1260°
α⇌β
Liq.
+
(α-Gd)
845°
70
>99.4
(α-Fe) + Fe17Gd2
0 10 20 30 40 50 60 70 80 90 100
At % Gd

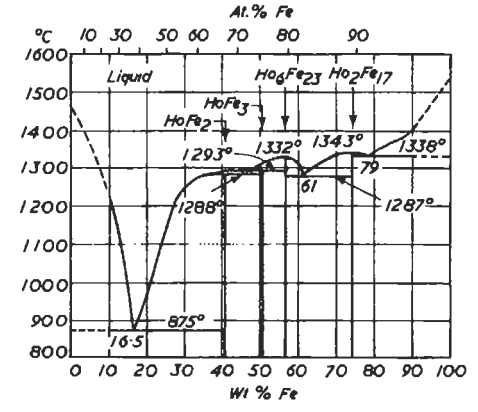
Fe–Ge


Wt % Ge
°C
10 20 30 40 50 60 70 80 90
1600
1535°
1500
Fe3Ge
FeGe
FeGe2
1400
1300
Liquid
1200
1170°
37.5
γ - Fe
1130°
34
34.5
1100
1000
937°
900
α - Fe
β
845°
866°
859°
43
~64.5
~75.5
800
(β - Fe3Ge)
700-800°
δ
700
610 - 710°
600
(α - Fe3Ge)
500
400
0 10 20 30 40 50 60 70 80 90 100
At % Ge

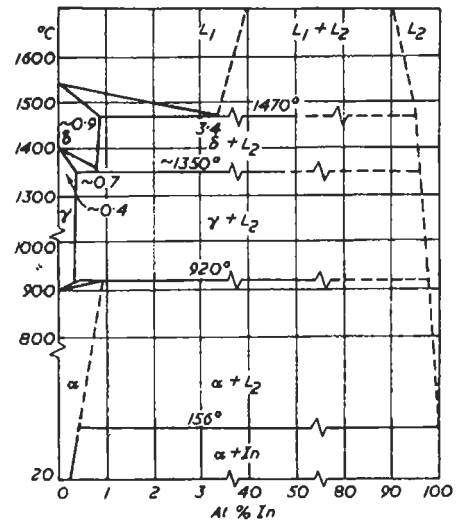
Fe–Hf


Wt. % Hf
°C
Liquid
HfFe2
Hf2Fe
1810 ± 20°
α ⇌ β
1535°
7·9
1350 ± 10°
1330 ± 5°
0·89
0·51
1300 ± 10°
1235 ± 10°
63·9
>96·9
935 ± 5°
0·06
768°
~370°
~200°
At. % Hf

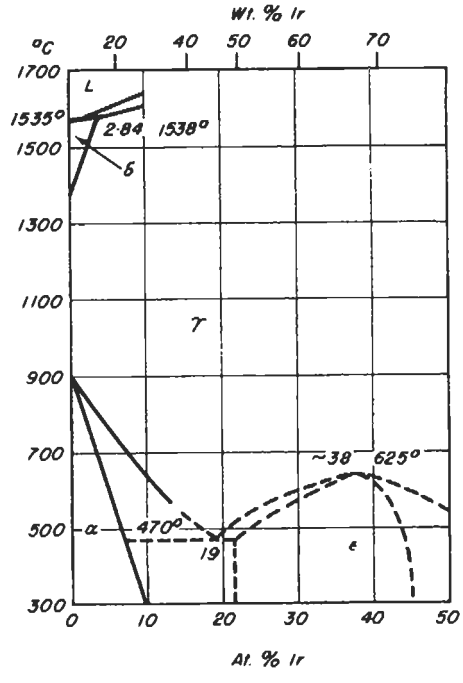
Fe–Ho


At. % Fe
°C
Liquid
Ho6Fe23
Ho2Fe17
HoFe3
HoFe2
1293°
1332°
1343°
1338°
79
61
1288°
1287°
875°
16·5
Wt % Fe

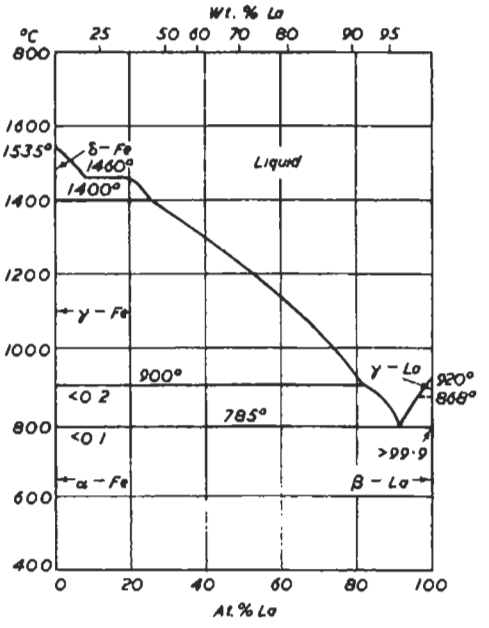
Fe–In


°C
1600
1500
1400
1300
1000
900
800
20
L_1
$L_1 + L_2$
L_2
1470°
3·4
0·9
δ
$\delta + L_2$
~1350°
~0·7
~0·4
γ
$\gamma + L_2$
920°
α
$\alpha + L_2$
156°
$\alpha + In$
0 1 2 3 40 50 80 90 100
At % In

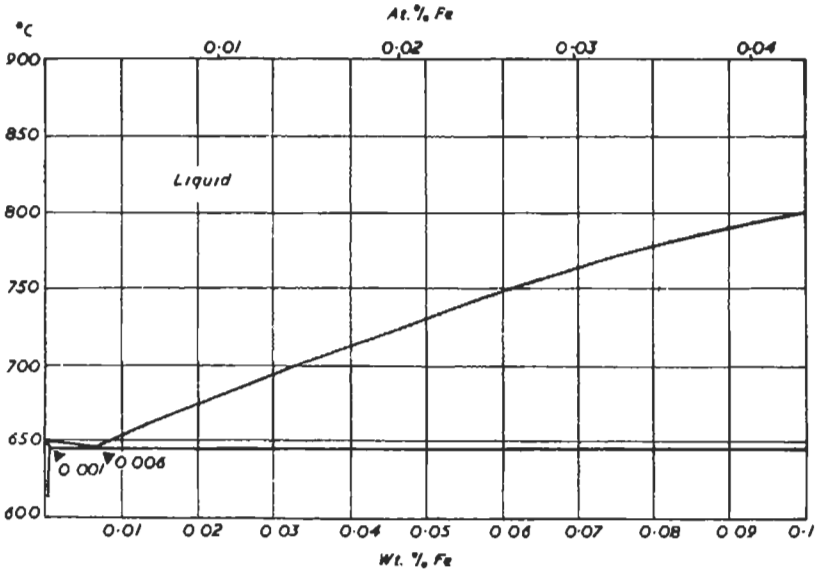
Fe–Ir


Wt. % Ir
°C
20 40 50 60 70
1700
1535°
1500
1300
1100
900
700
500
300
L
2·84
1538°
δ
γ
~38
625°
α
470°
19
ε
0 10 20 30 40 50
At. % Ir

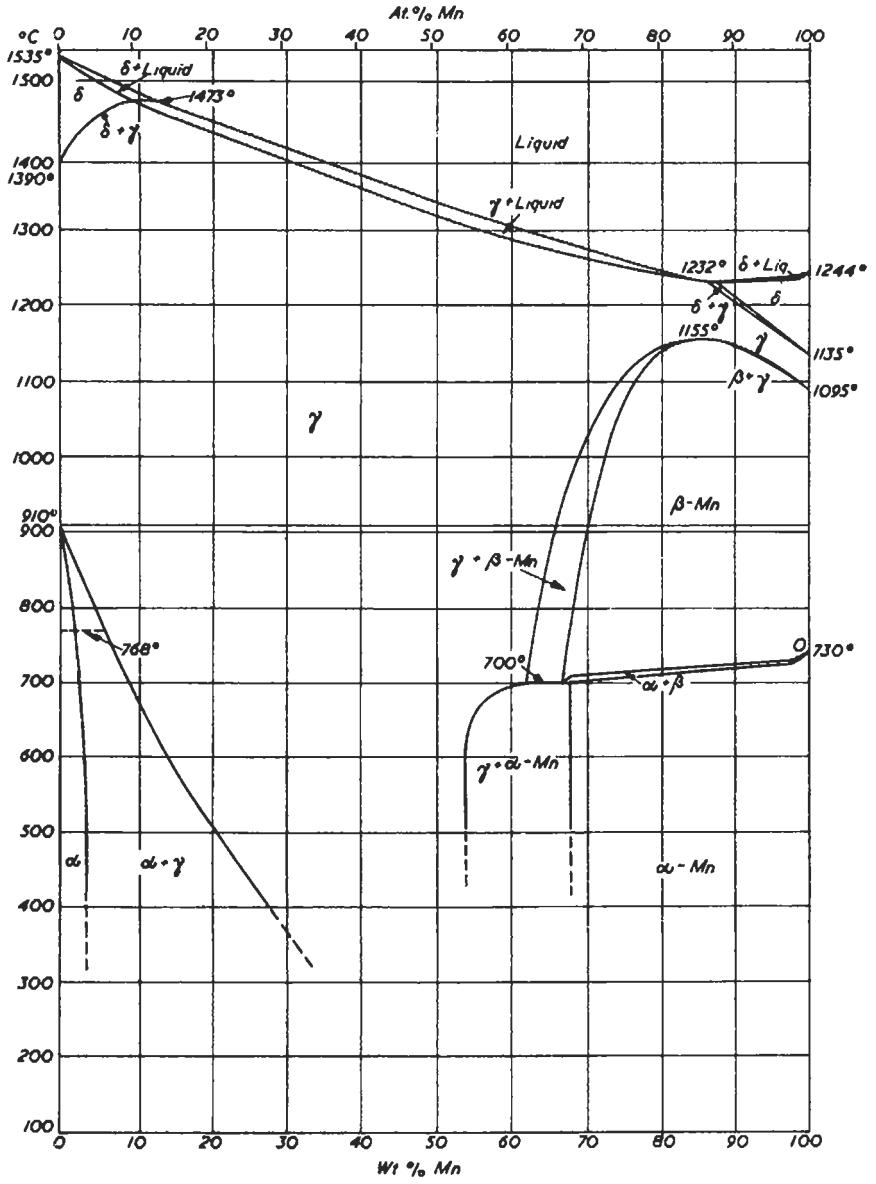
Fe–La


Wt. % La
°C
25
50 60 70 80
90 95
800
1600
1535°
δ – Fe
1460°
1400°
Liquid
1400
1200
γ – Fe
1000
900°
γ – La
920°
868°
<0·2
785°
800
<0·1
>99·9
α – Fe
β – La
600
400
0
20
40
60
80
100
At. % La

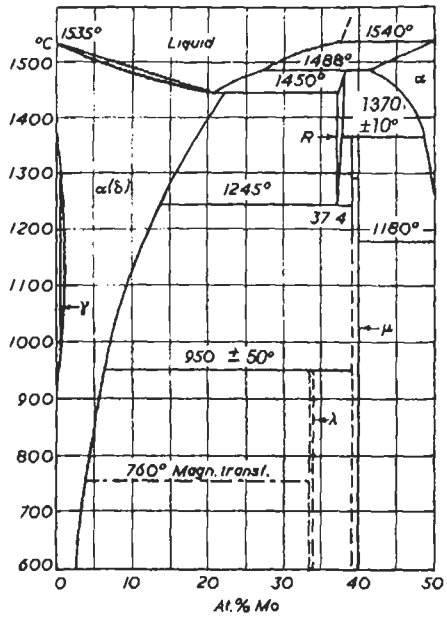
Fe–Mg


At. % Fe
°C
0·01
0·02
0·03
0·04
900
850
Liquid
800
750
700
650
0 001
0 006
600
0·01
0 02
0 03
0·04
0·05
0 06
0·07
0·08
0 09
0·1
Wt. % Fe

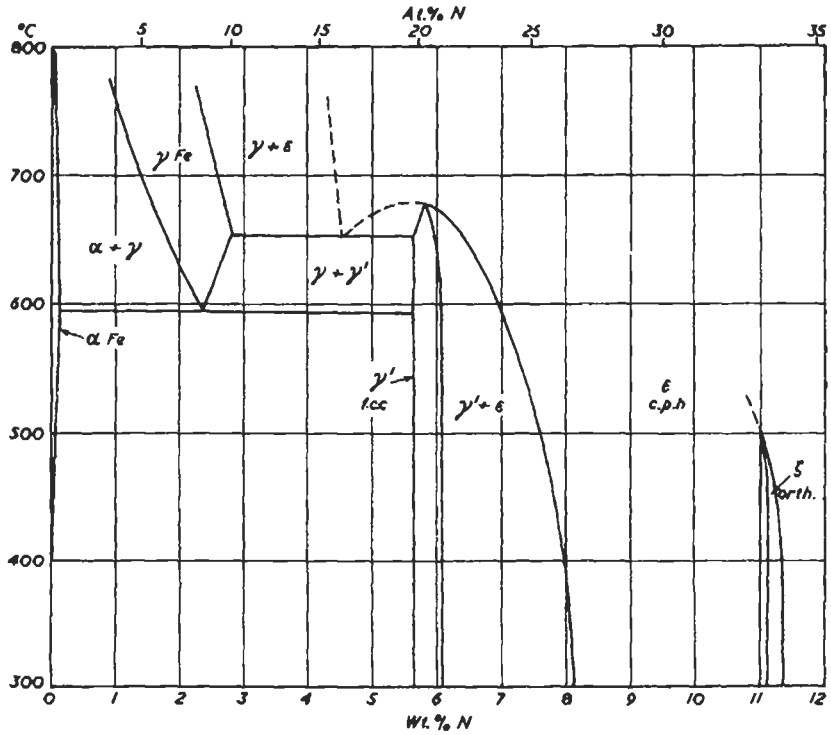
Fe–Mn


At.% Mn
°C
1535°
1500
1400
1390°
1300
1200
1100
1000
910°
900
800
700
600
500
400
300
200
100
δ + Liquid
1473°
δ
δ + γ
Liquid
γ + Liquid
1232°
δ + Liq.
1244°
δ + γ
δ
1155°
γ
1135°
β + γ
1095°
γ
β-Mn
γ + β-Mn
768°
700°
730°
α + β
γ + α-Mn
α
α + γ
α - Mn
0 10 20 30 40 50 60 70 80 90 100
Wt % Mn

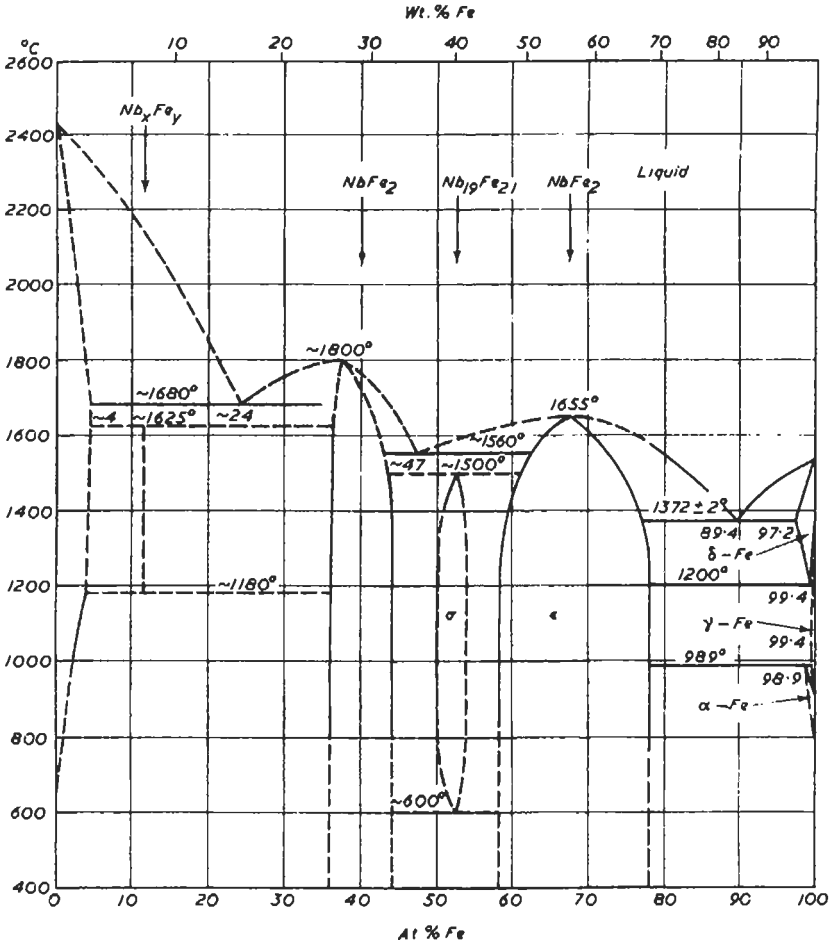
Fe–Mo


°C
1535°
Liquid
1540°
1488°
1450°
α
1370°
±10°
R
α(δ)
1245°
37 4
1180°
γ
μ
950 ± 50°
λ
760° Magn. transl.
1500
1400
1300
1200
1100
1000
900
800
700
600
0
10
20
30
40
50
At.% Mo

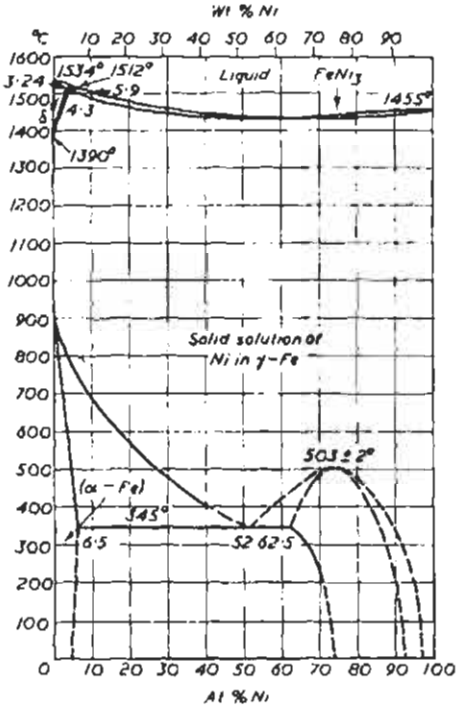
Fe–N


At.% N
°C
5
10
15
20
25
30
35
γ Fe
γ + ε
α + γ
γ + γ'
α Fe
γ'
f.cc
γ' + ε
ε
c.p.h
ζ
orth.
800
700
600
500
400
300
0
1
2
3
4
5
6
7
8
9
10
11
12
Wt.% N

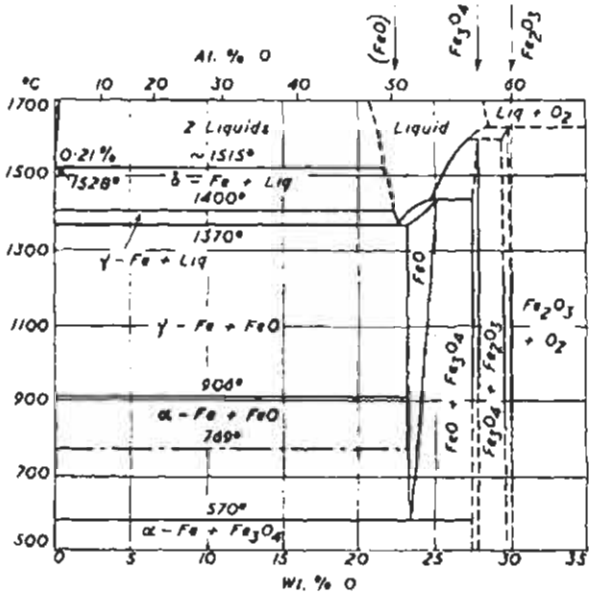
Fe–Nb


Wt. % Fe
°C
10
20
30
40
50
60
70
80
90
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
Nb_xFe_y
$NbFe_2$
$Nb_{19}Fe_{21}$
$NbFe_2$
Liquid
~1800°
~1680°
~4
~1625°
~24
~1560°
~47
~1500°
1655°
1372 ± 2°
89·4
97·2
δ – Fe
1200°
~1180°
99·4
γ – Fe
99·4
989°
98·9
α – Fe
σ
~600°
0
10
20
30
40
50
60
70
80
90
100
At % Fe

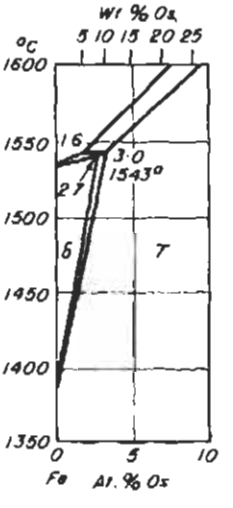
Fe–Ni



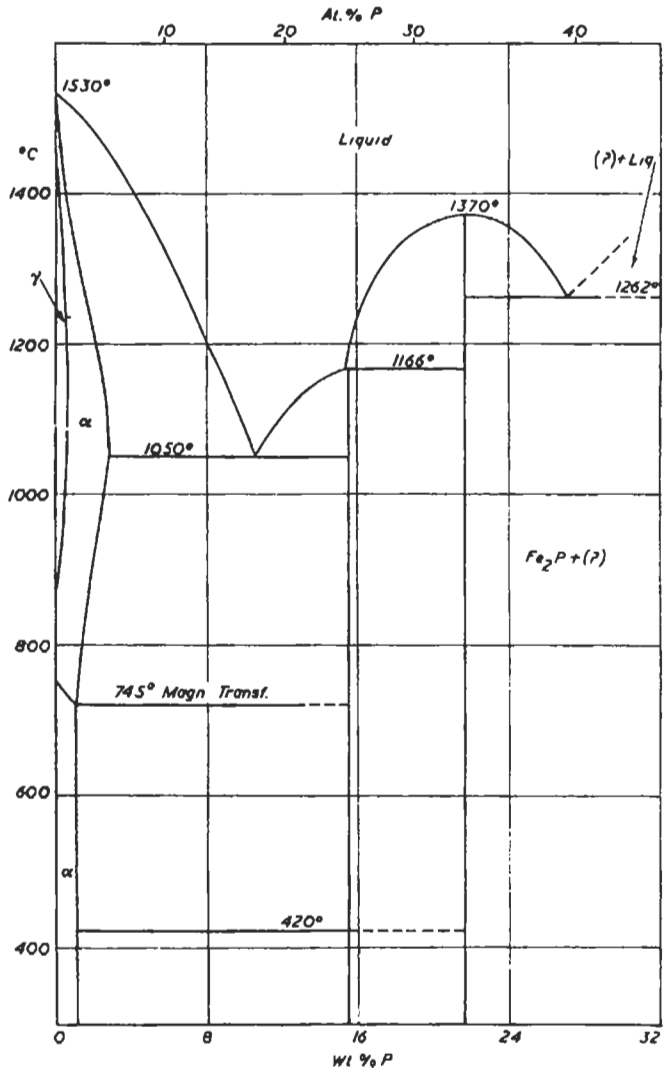
Fe–O



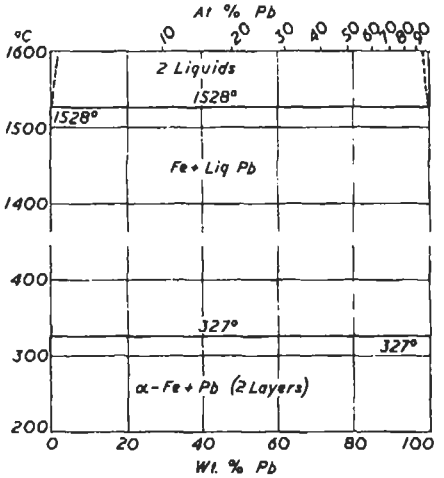
Fe–Os



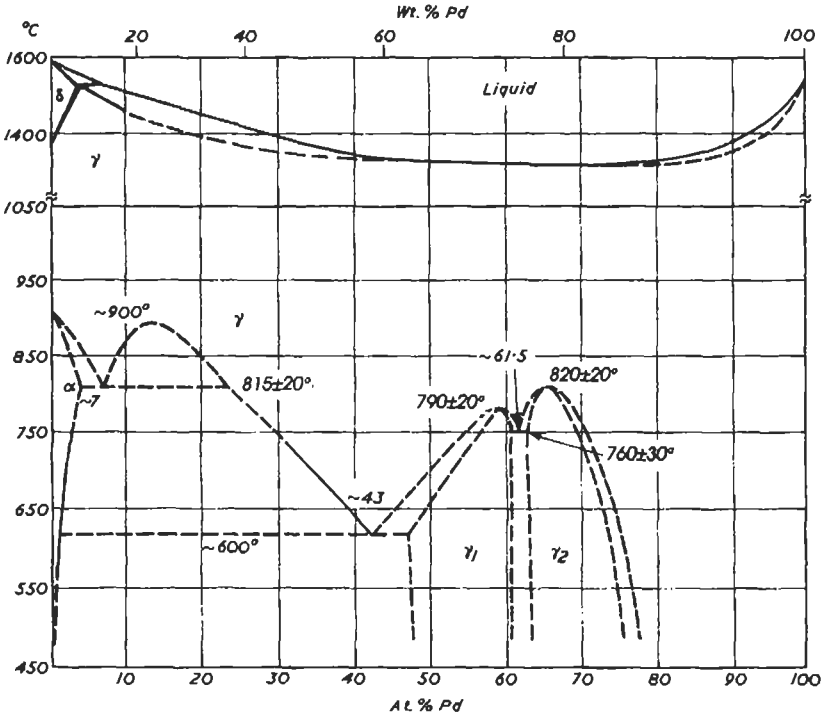
Fe–P


At.% P
10
20
30
40
1530°
Liquid
°C
(?)+Liq
1400
1370°
γ
1262°
1200
1166°
α
1050°
1000
Fe2P+(?)
800
745° Magn Transf.
600
α
420°
400
0
8
16
24
32
Wt % P

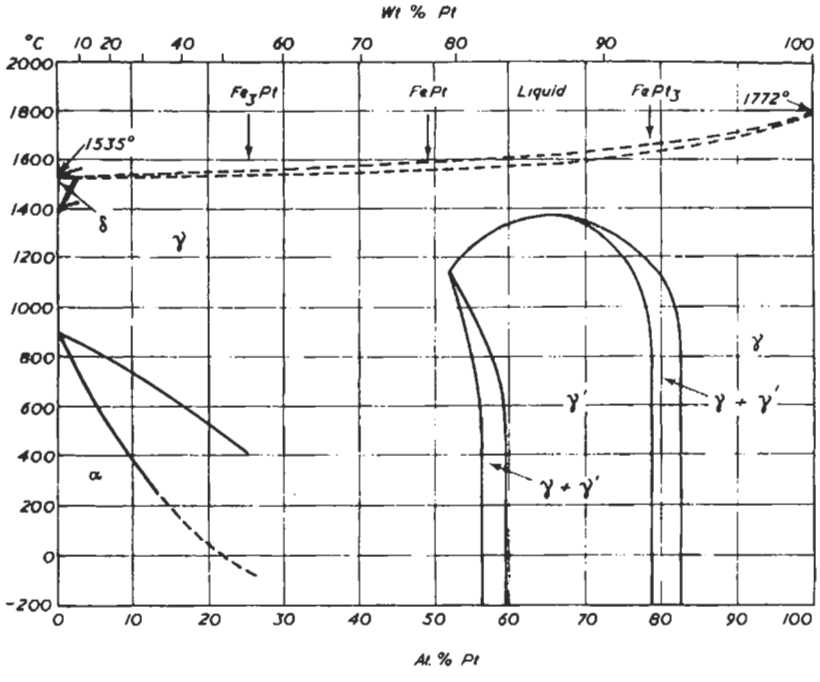
Fe–Pb


At % Pb
°C
1600
1500
1400
400
300
200
2 Liquids
1528°
1528°
Fe + Liq Pb
327°
327°
α - Fe + Pb (2 Layers)
0
20
40
60
80
100
Wt. % Pb

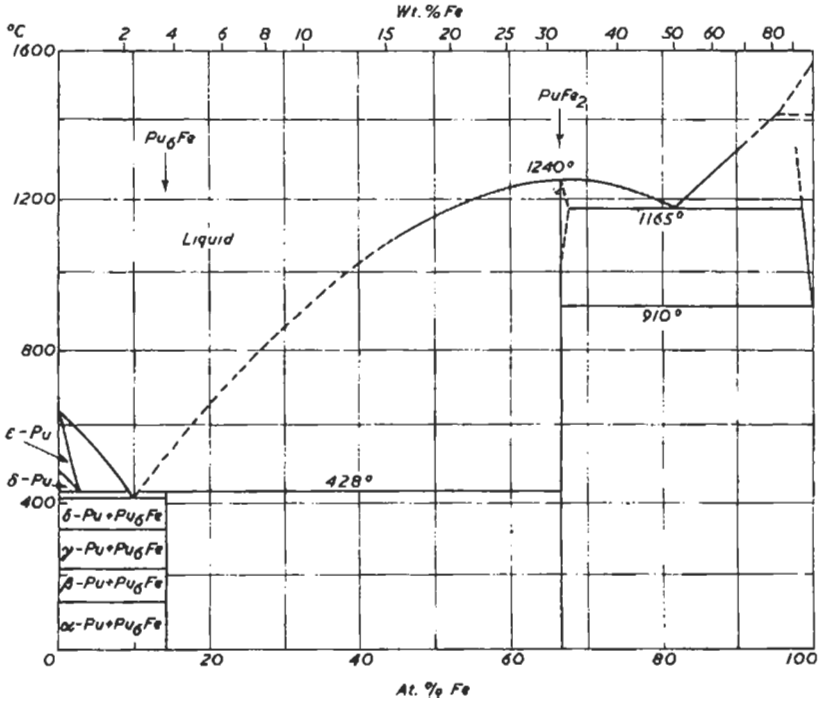
Fe–Pd


Wt. % Pd
°C
20
40
60
80
100
1600
1400
1050
950
850
750
650
550
450
δ
γ
Liquid
~900°
γ
α
~7
815±20°
~61·5
820±20°
790±20°
760±30°
~43
~600°
γ1
γ2
10
20
30
40
50
60
70
80
90
100
At % Pd

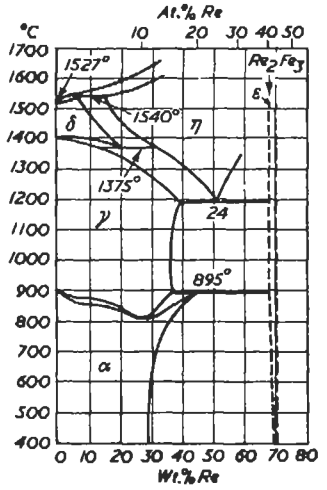
Fe–Pt


Wt % Pt
°C
10 20 40 60 70 80 90 100
2000
1800
1600
1400
1200
1000
800
600
400
200
0
-200
Fe_3Pt
FePt
Liquid
$FePt_3$
1772°
1535°
δ
γ
α
γ'
γ + γ'
γ + γ'
0 10 20 30 40 50 60 70 80 90 100
At. % Pt

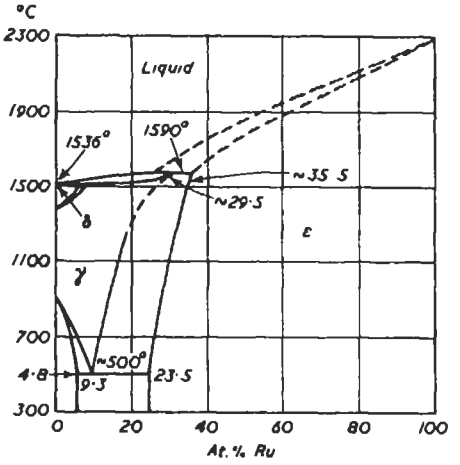
Fe–Pu


Wt. % Fe
°C
2 4 6 8 10 15 20 25 30 40 50 60 80
1600
1200
800
400
Pu_6Fe
$PuFe_2$
1240°
1165°
910°
Liquid
ε-Pu
δ-Pu
428°
δ-Pu + Pu_6Fe
γ-Pu + Pu_6Fe
β-Pu + Pu_6Fe
α-Pu + Pu_6Fe
0 20 40 60 80 100
At. % Fe

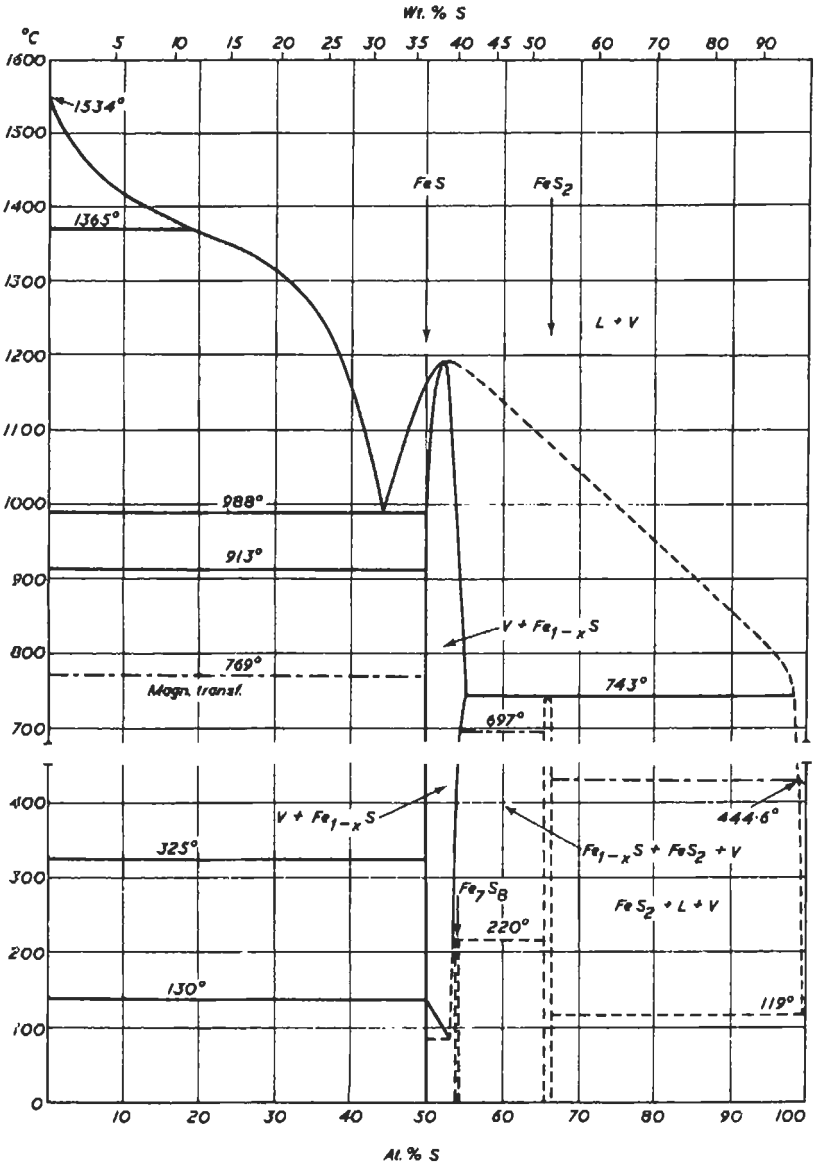
Fe–Re


At.% Re
°C
10 20 30 40 50
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
1527°
1540°
1375°
δ
η
γ
24
895°
α
Re2Fe3
ε
0 10 20 30 40 50 60 70 80
Wt.% Re

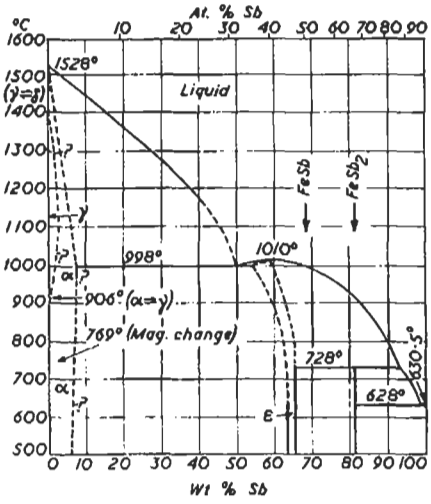
Fe–Ru


°C
2300
1900
1500
1100
700
300
Liquid
1536°
1590°
~35 S
~29·5
δ
ε
γ
~500°
4·8
9·3
23·5
0 20 40 60 80 100
At.% Ru

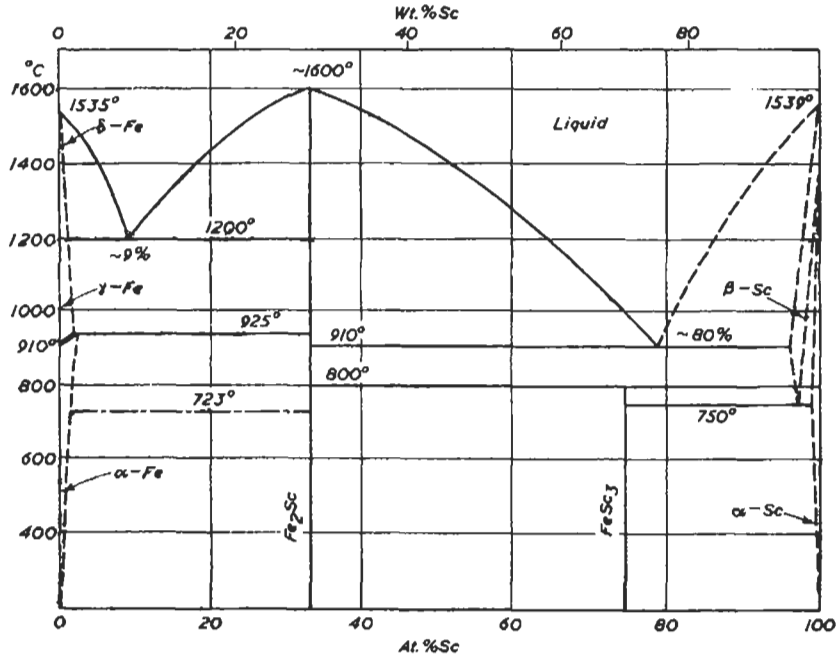
Fe–S


Wt. % S
°C
5 10 15 20 25 30 35 40 45 50 60 70 80 90
1600
1500
1400
1300
1200
1100
1000
900
800
700
1534°
1365°
FeS
FeS2
L + V
988°
913°
V + Fe1−xS
769°
Magn. transf.
743°
697°
400
300
200
100
0
325°
V + Fe1−xS
Fe1−xS + FeS2 + V
444·6°
Fe7S8
220°
FeS2 + L + V
130°
119°
10 20 30 40 50 60 70 80 90 100
At. % S

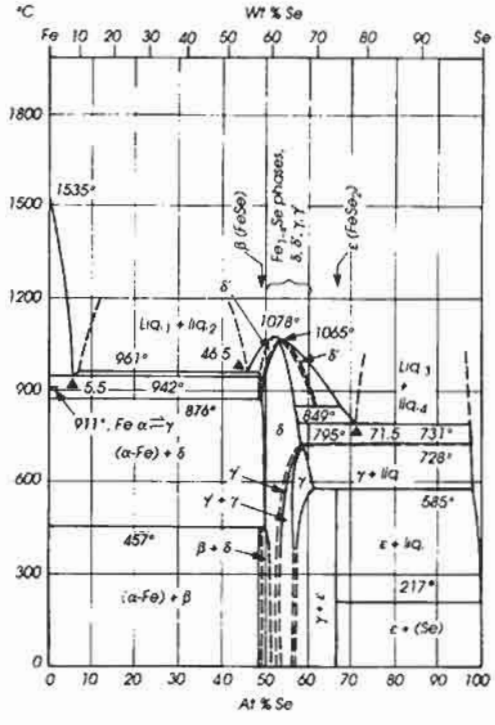
Fe–Sb


°C
At. % Sb
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
10 20 30 40 50 60 70 80 90
1528°
(γ⇌δ)
Liquid
FeSb
FeSb2
γ
β
α
998°
1010°
906° (α⇌γ)
769° (Mag. change)
728°
630.5°
628°
ε
0 10 20 30 40 50 60 70 80 90 100
Wt % Sb

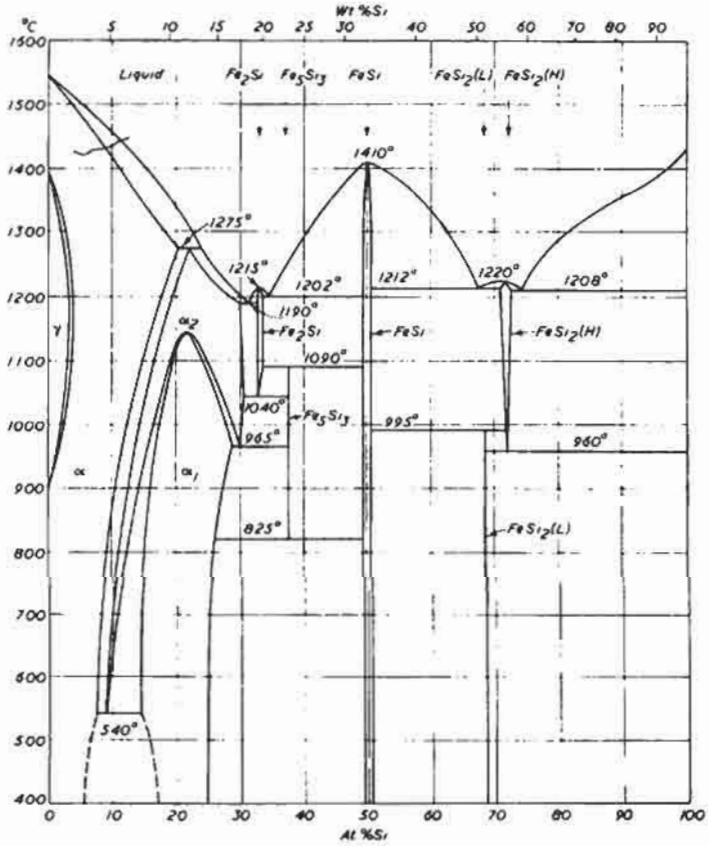
Fe–Sc


Wt.%Sc
0 20 40 60 80
°C
1600
1400
1200
1000
910°
800
600
400
~1600°
1535°
δ–Fe
Liquid
1539°
1200°
~9%
γ–Fe
β–Sc
925°
910°
~80%
800°
723°
750°
α–Fe
Fe2Sc
FeSc3
α–Sc
0 20 40 60 80 100
At.%Sc

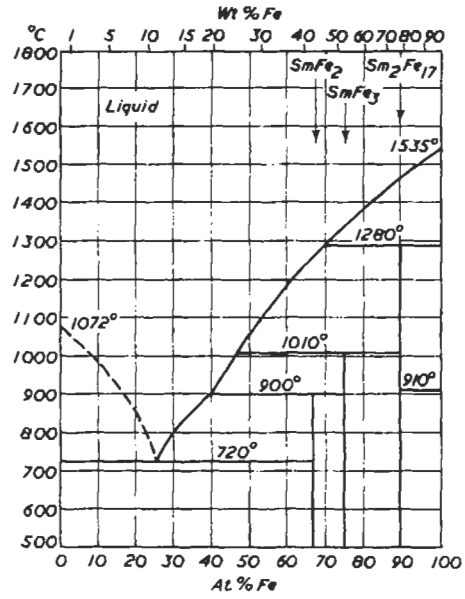
Fe–Se


°C
Wt % Se
Fe
Se
1535°
β (FeSe)
Fe1−xSe phases
δ, δ', γ, γ'
ε (FeSe2)
δ'
Liq.1 + liq.2
1078°
1065°
961°
46.5
5.5
942°
876°
911°, Fe α ⇌ γ
(α-Fe) + δ
849°
795°
71.5
731°
728°
Liq.1 + liq.2
γ + liq
585°
457°
β + δ
(α-Fe) + β
ε + liq.
217°
ε + (Se)
At % Se

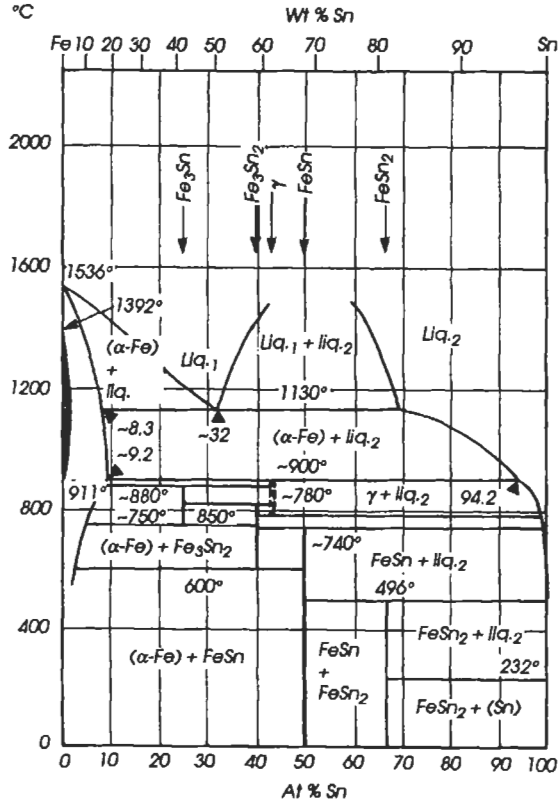
Fe–Si


°C
Wt %Si
Liquid
Fe2Si
Fe5Si3
FeSi
FeSi2(L)
FeSi2(H)
1410°
1275°
1215°
1202°
1212°
1220°
1208°
1190°
1090°
1040°
995°
965°
960°
825°
540°
γ
α2
α1
α
At %Si

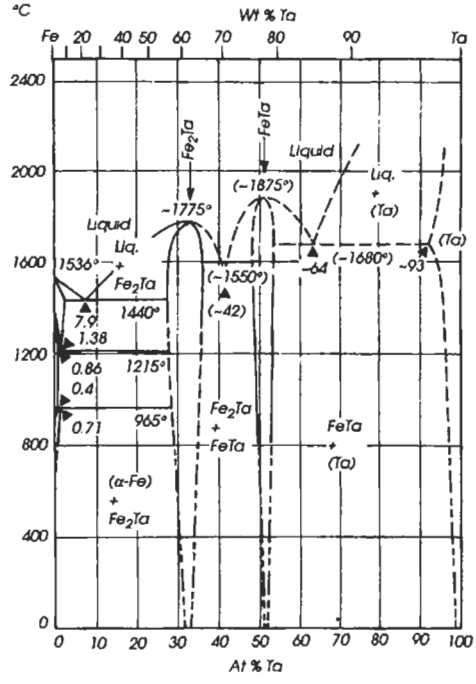
Fe–Sm


Wt % Fe
°C
1 5 10 15 20 30 40 50 60 70 80 90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
SmFe2
Sm2Fe17
SmFe3
Liquid
1535°
1280°
1072°
1010°
900°
910°
720°
0 10 20 30 40 50 60 70 80 90 100
At % Fe

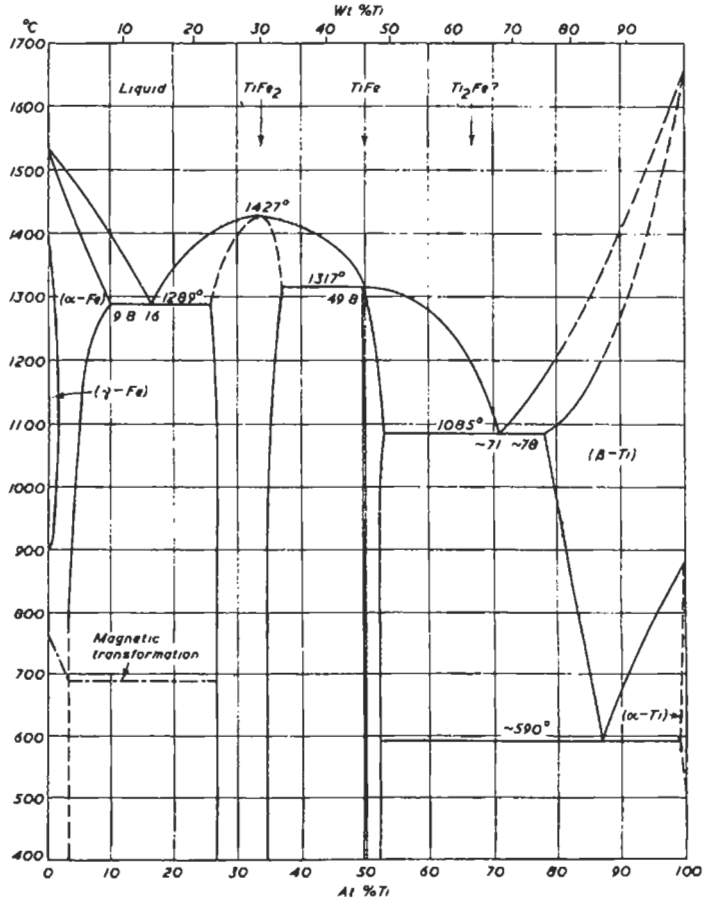
Fe–Sn


°C
Wt % Sn
Fe 10 20 30 40 50 60 70 80 90 Sn
2000
1600
1200
800
400
0
Fe3Sn
Fe3Sn2
γ
FeSn
FeSn2
1536°
1392°
(α-Fe)
+
liq.
Liq.1
Liq.1 + liq.2
Liq.2
1130°
~8.3
~9.2
~32
(α-Fe) + liq.2
~900°
911°
~880°
~750°
850°
~780°
γ + liq.2
94.2
(α-Fe) + Fe3Sn2
600°
~740°
FeSn + liq.2
496°
FeSn2 + liq.2
232°
(α-Fe) + FeSn
FeSn
+
FeSn2
FeSn2 + (Sn)
0 10 20 30 40 50 60 70 80 90 100
At % Sn

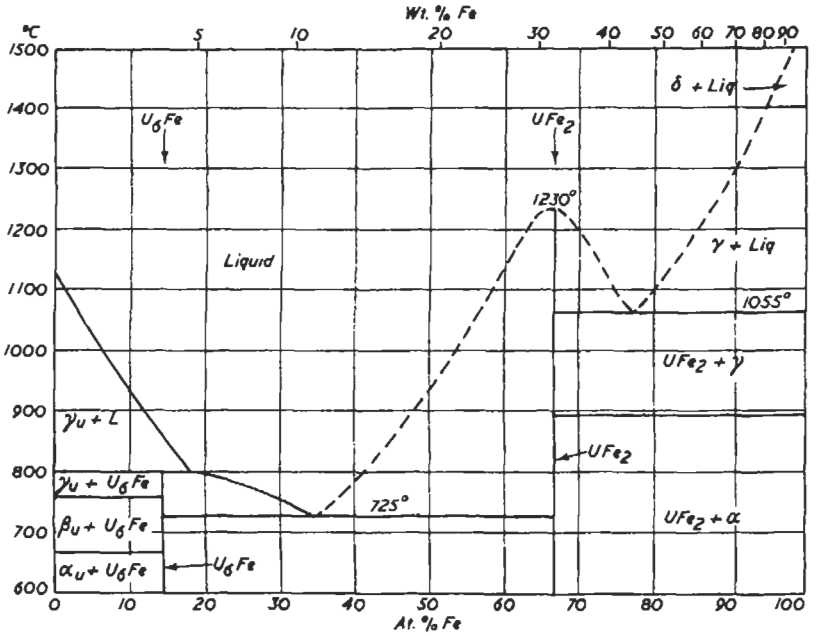
Fe–Ta


°C
Wt % Ta
Fe 20 40 50 60 70 80 90 Ta
2400
2000
1600
1200
800
400
0
Liquid
Liq. + Fe2Ta
Fe2Ta
FeTa
Liquid
Liq. + (Ta)
(Ta)
~1775°
(~1875°)
1536°
1440°
(~1550°)
(~42)
~64
(~1680°)
~93
7.9
1.38
0.86
1215°
0.4
0.71
965°
Fe2Ta + FeTa
FeTa + (Ta)
(α-Fe) + Fe2Ta
0 10 20 30 40 50 60 70 80 90 100
At % Ta

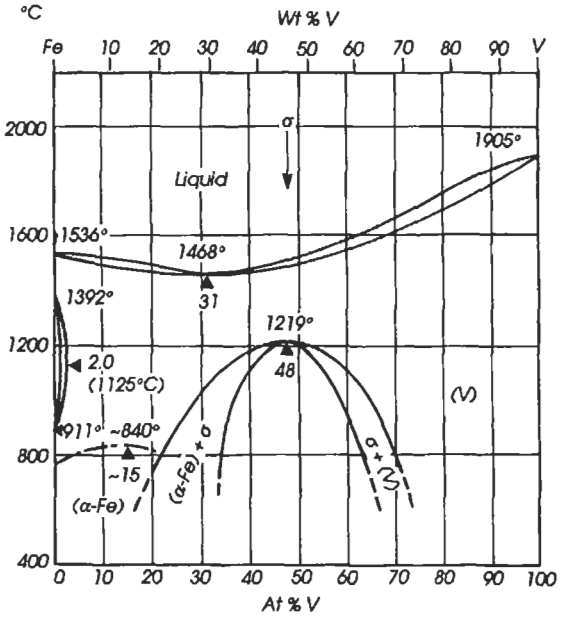
Fe–Ti


°C
Wt %Ti
10 20 30 40 50 60 70 80 90
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
Liquid
TiFe2
TiFe
Ti2Fe?
1427°
1317°
49 8
(α-Fe)
1289°
9 8 16
(γ-Fe)
1085°
~71 ~78
(β-Ti)
Magnetic transformation
~590°
(α-Ti)
0 10 20 30 40 50 60 70 80 90 100
At %Ti

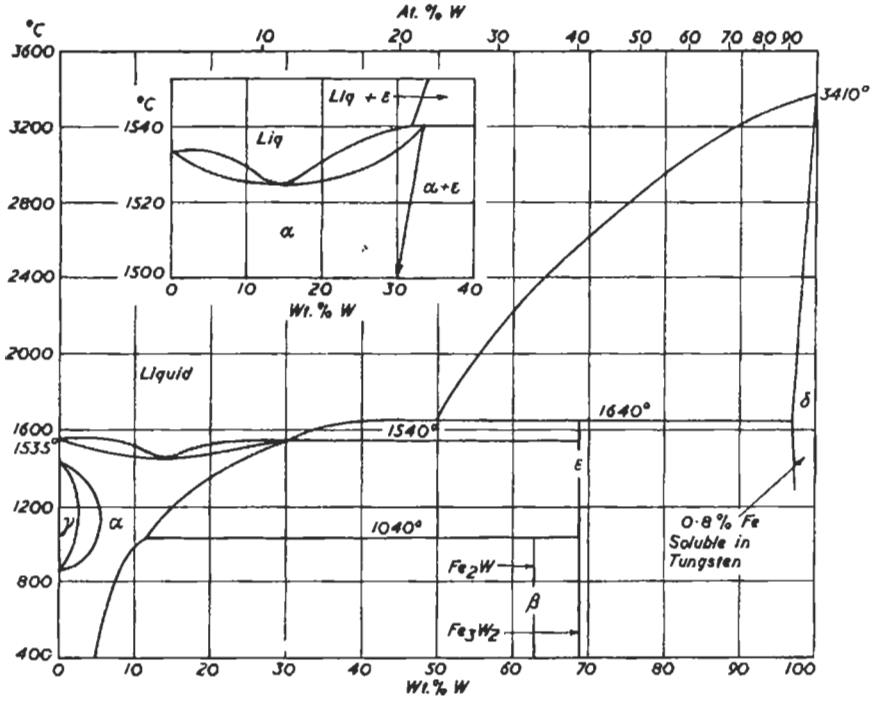
Fe–U


Wt. % Fe
°C
5
10
20
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
900
800
700
600
U_6Fe
UFe_2
δ + Liq
1230°
Liquid
γ + Liq
1055°
UFe_2 + γ
γ_u + L
UFe_2
γ_u + U_6Fe
725°
UFe_2 + α
β_u + U_6Fe
α_u + U_6Fe
U_6Fe
0
10
20
30
40
50
60
70
80
90
100
At. % Fe

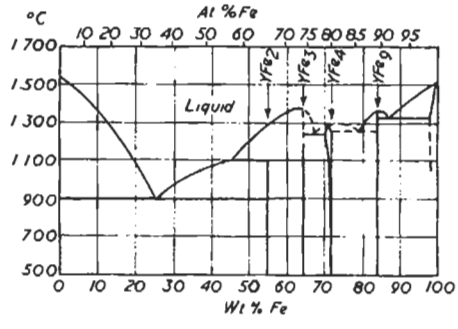
Fe–V


°C
Wt % V
Fe
10
20
30
40
50
60
70
80
90
V
2000
1600
1200
800
400
σ
1905°
Liquid
1536°
1468°
31
1392°
1219°
48
2.0
(1125°C)
911°
~840°
~15
(α-Fe)
(α-Fe) + σ
σ + β
(V)
0
10
20
30
40
50
60
70
80
90
100
At % V

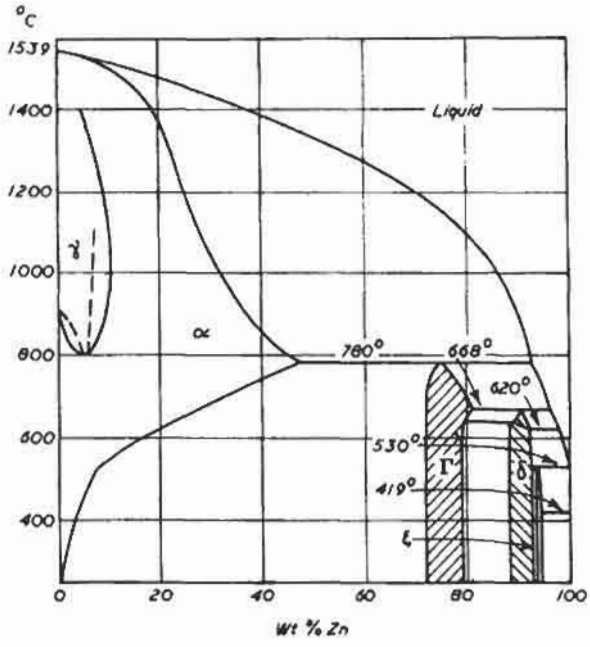
Fe–W


At. % W
°C
Liq + ε
Liq
α+ε
α
Wt. % W
Liquid
1640°
1540°
3410°
δ
ε
γ
α
1040°
0·8 % Fe
Soluble in
Tungsten
Fe2W
β
Fe3W2
Wt. % W

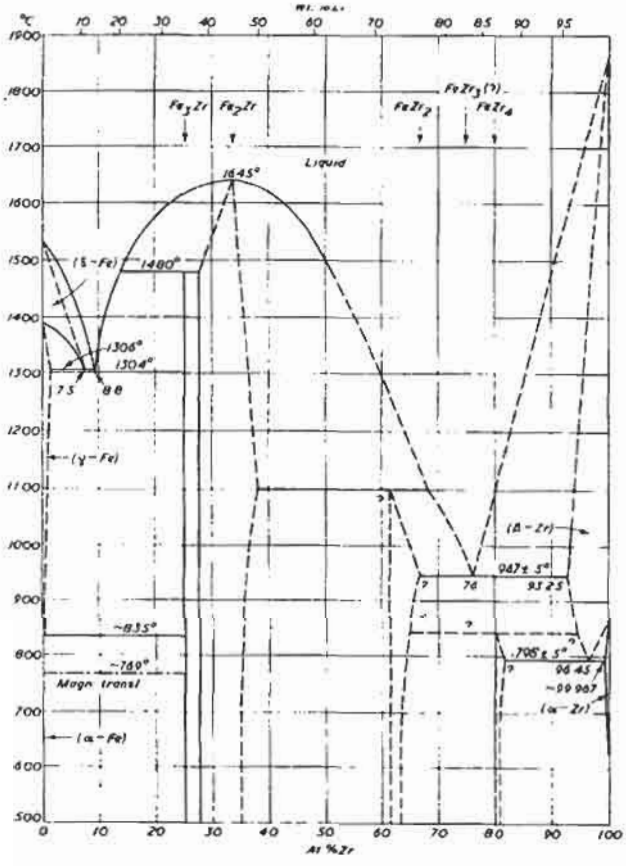
Fe–Y


°C
At % Fe
Liquid
Yfe2
Yfe3
Yfe4
Yfe9
Wt % Fe

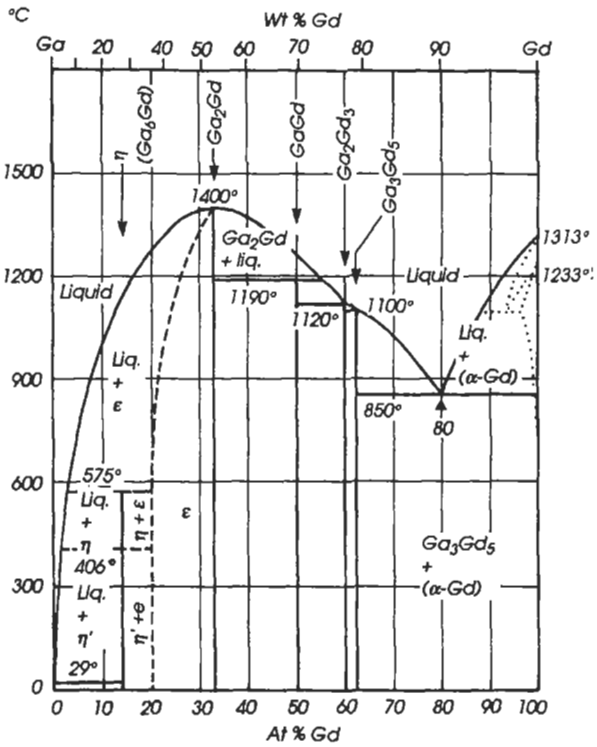
Fe–Zn


°C
1539
1400
1200
1000
800
600
400
Liquid
γ
α
780°
668°
620°
530°
Γ
δ
419°
ζ
0
20
40
60
80
100
Wt % Zn

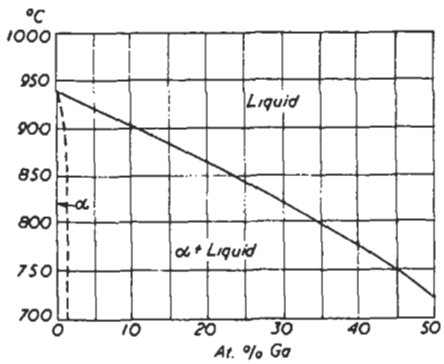
Fe–Zr


°C
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
Fe3Zr
Fe2Zr
FeZr2
FeZr3 (?)
FeZr4
Liquid
1645°
(δ-Fe)
1480°
1306°
1304°
(γ-Fe)
~835°
~769°
Magn. transf.
(α-Fe)
(β-Zr)
98.45
~99.967
(α-Zr)
0
10
20
30
40
50
60
70
80
90
100
At %Zr

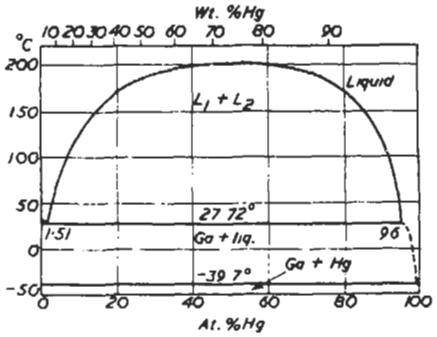
Ga–Gd



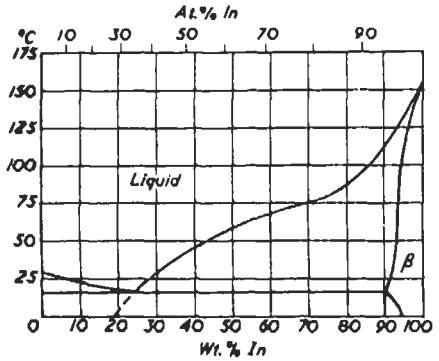
Ga–Ge



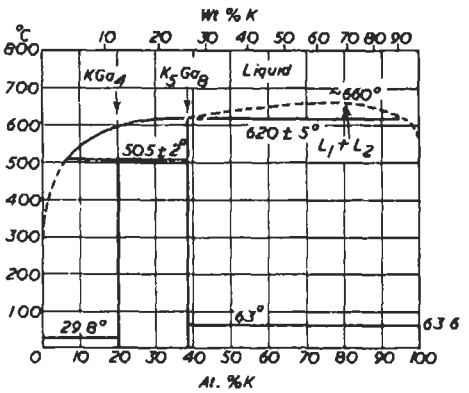
Ga–Hg



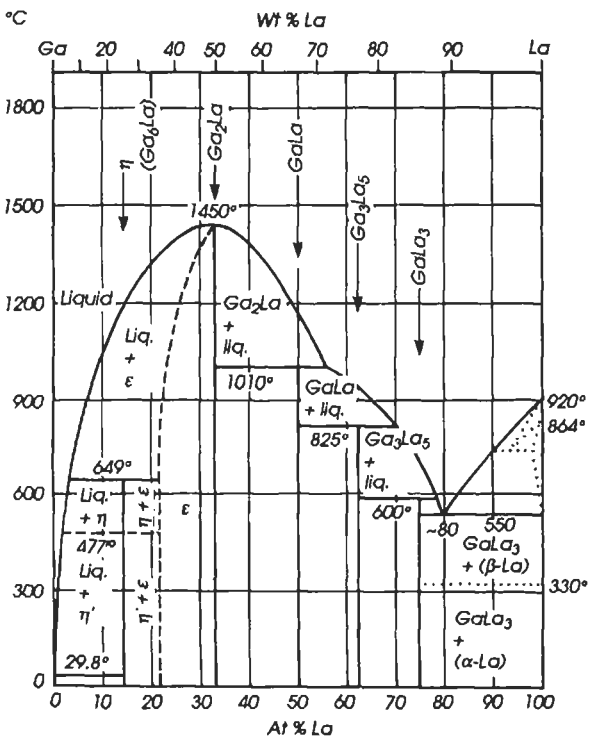
Ga–In



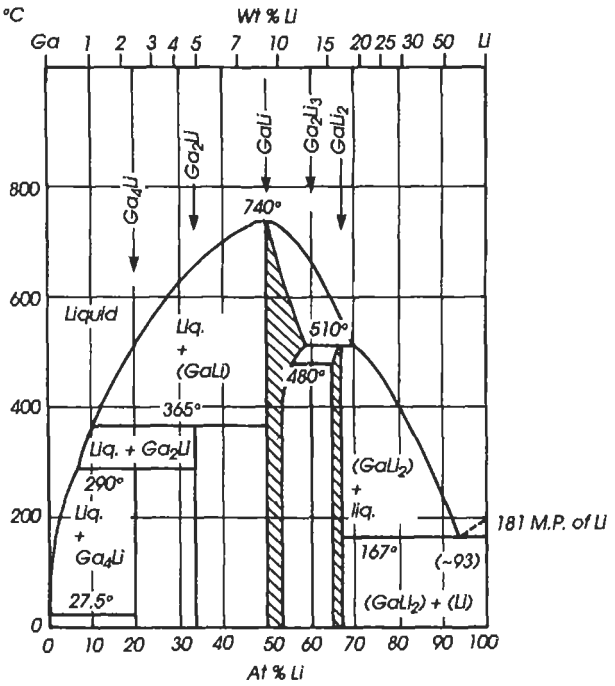
Ga–K



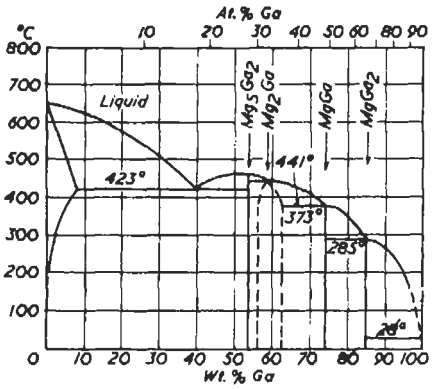
Ga–La



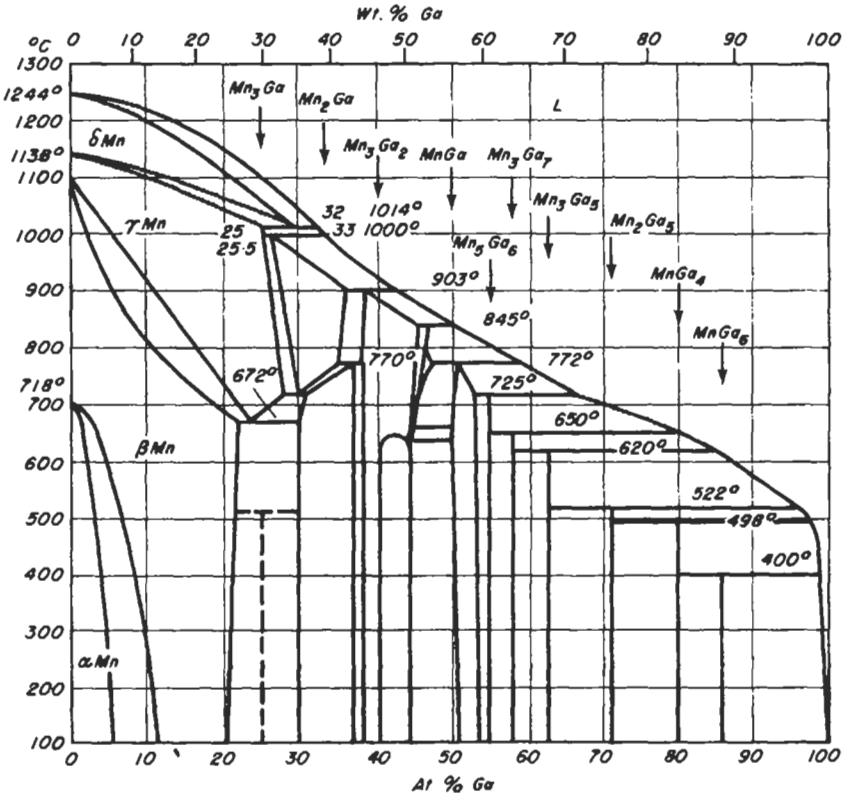
Ga–Li


°C
Wt % Li
Ga 1 2 3 4 5 7 10 15 20 25 30 50 Li
Ga_4Li
Ga_2Li
GaLi
Ga_2Li_3
$GaLi_2$
800
600
400
200
0
740°
Liquid
Liq. + (GaLi)
510°
480°
365°
Liq. + Ga_2Li
290°
Liq. + Ga_4Li
27.5°
($GaLi_2$) + liq.
181 M.P. of Li
167°
(~93)
($GaLi_2$) + (Li)
0 10 20 30 40 50 60 70 80 90 100
At % Li

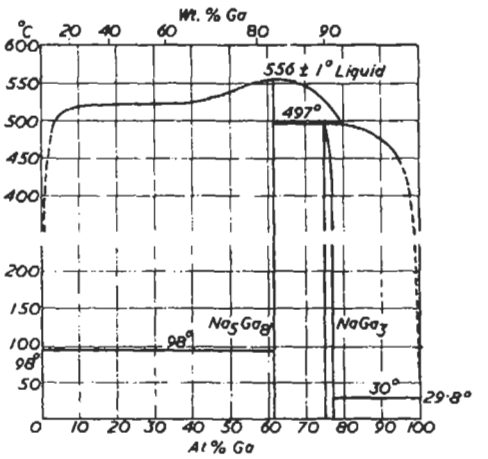
Ga–Mg


At. % Ga
°C
10 20 30 40 50 60 80 90
800
700
600
500
400
300
200
100
0
Liquid
Mg_5Ga_2
Mg_2Ga
MgGa
$MgGa_2$
441°
423°
373°
285°
28°
0 10 20 30 40 50 60 70 80 90 100
Wt. % Ga

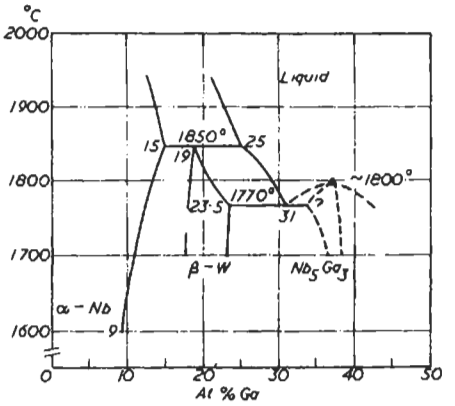
Ga–Mn


Wt. % Ga
°C
1300
1244°
1200
1138°
1100
1000
900
800
718°
700
600
500
400
300
200
100
0 10 20 30 40 50 60 70 80 90 100
Mn3Ga
Mn2Ga
L
δMn
Mn3Ga2
MnGa
Mn3Ga7
Mn3Ga5
Mn2Ga5
Mn5Ga6
MnGa4
MnGa6
γMn
32
1014°
33
1000°
25
25·5
903°
845°
772°
770°
725°
672°
650°
620°
βMn
522°
498°
400°
αMn
At % Ga

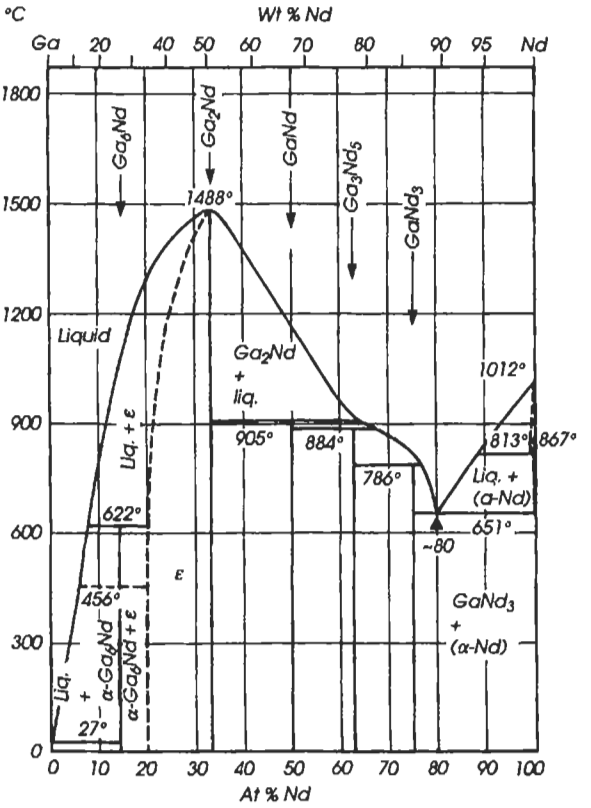
Ga–Na


Wt. % Ga
°C
600
550
500
450
400
200
150
100
98°
98°
50
20 40 60 80 90
556 ± 1° Liquid
497°
Na5Ga8
NaGa3
30°
29·8°
0 10 20 30 40 50 60 70 80 90 100
At % Ga

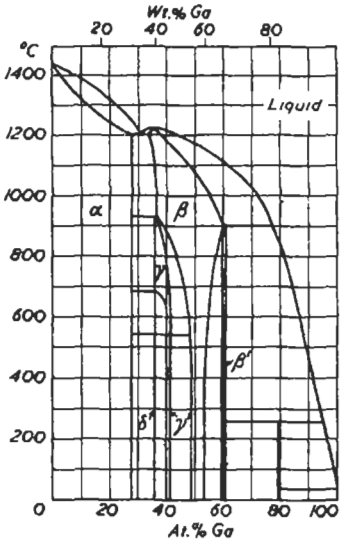
Ga–Nb


°C
2000
1900
1800
1700
1600
Liquid
1850°
15
19
25
1770°
23·5
31
~1800°
β – W
Nb5Ga3
α – Nb
9
0
10
20
30
40
50
At % Ga

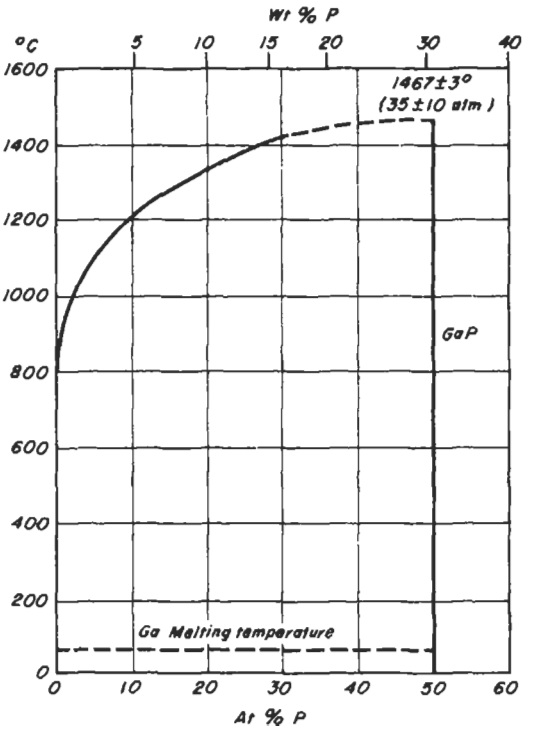
Ga–Nd


°C
Wt % Nd
Ga
20
40
50
60
70
80
90
95
Nd
1800
1500
1200
900
600
300
0
Ga6Nd
Ga2Nd
GaNd
Ga3Nd5
GaNd3
1488°
Liquid
Ga2Nd
+
liq.
905°
884°
786°
1012°
813°
867°
Liq. + ε
622°
Liq. + (α-Nd)
651°
~80
ε
456°
GaNd3
+
(α-Nd)
Liq.
+
α-Ga6Nd
α-Ga6Nd + ε
27°
0
10
20
30
40
50
60
70
80
90
100
At % Nd

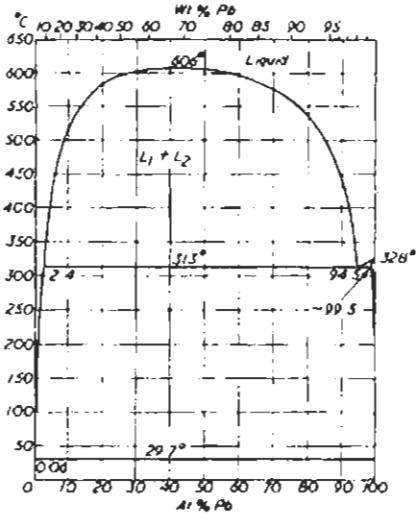
Ga–Ni


Wt.% Ga
20
40
60
80
°C
1400
1200
1000
800
600
400
200
0
Liquid
α
β
γ
β'
δ'
γ'
20
40
60
80
100
At.% Ga

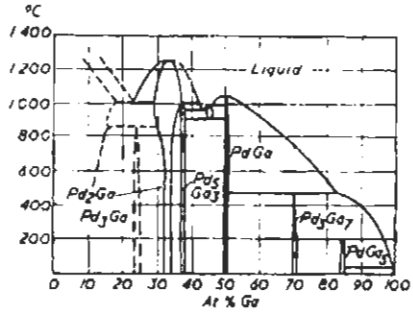
Ga–P


Wt % P
°C
5
10
15
20
30
40
1600
1400
1200
1000
800
600
400
200
0
1467±3°
(35±10 atm)
GaP
Ga Melting temperature
0
10
20
30
40
50
60
At % P

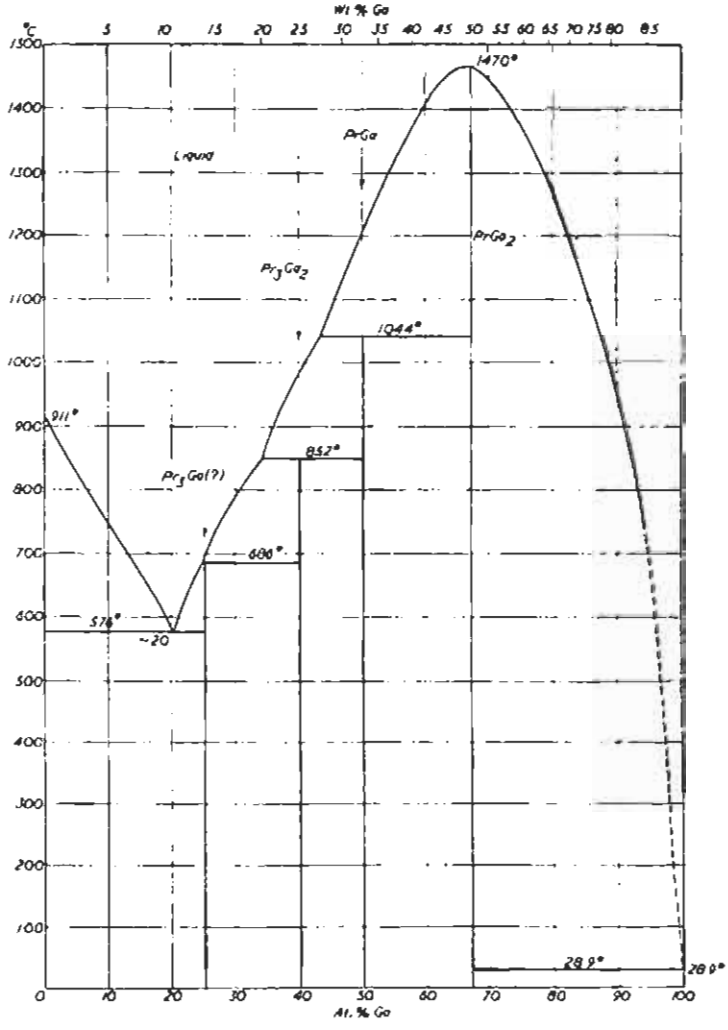
Ga–Pb



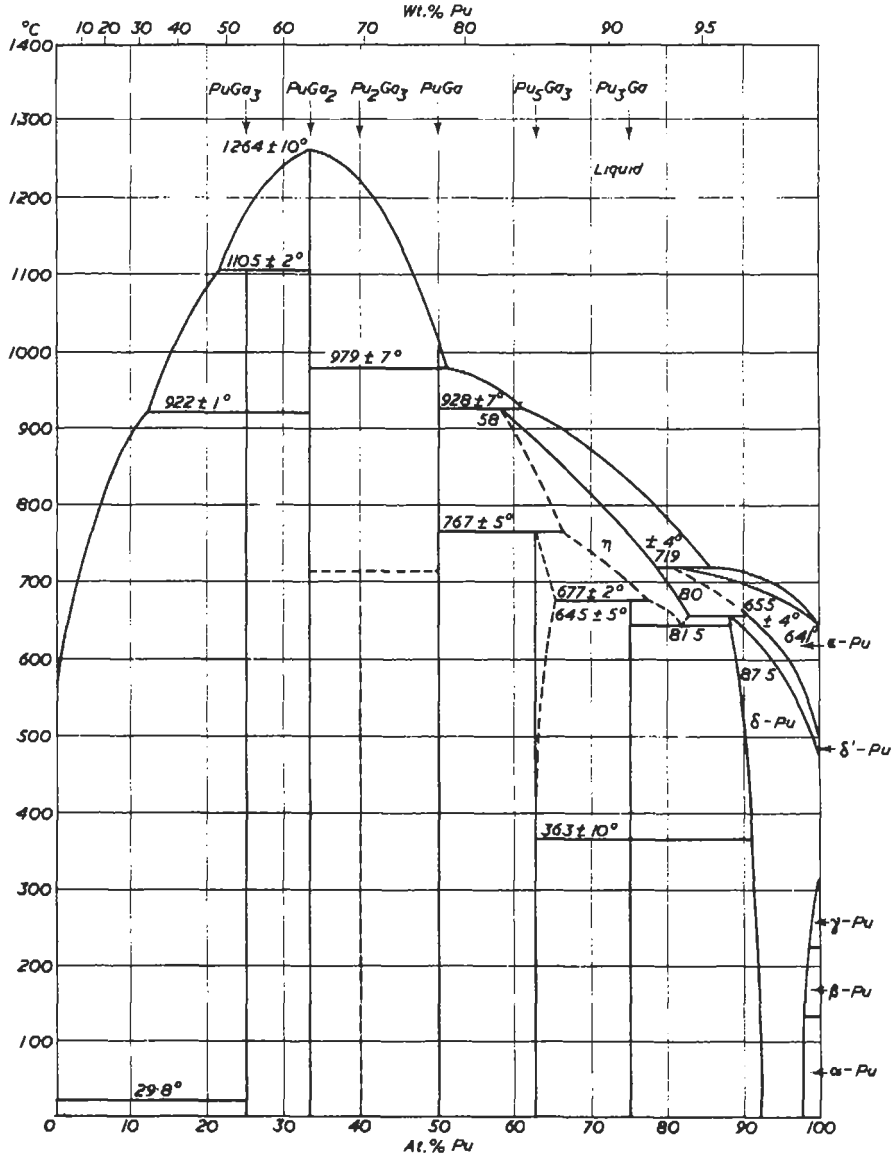
Ga–Pd



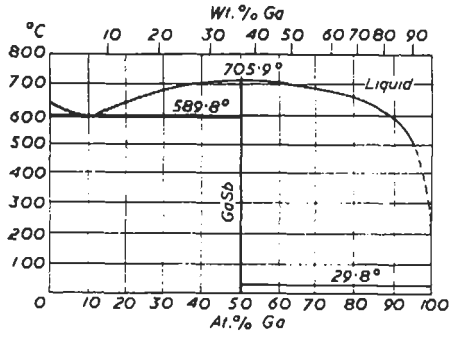
Ga–Pr



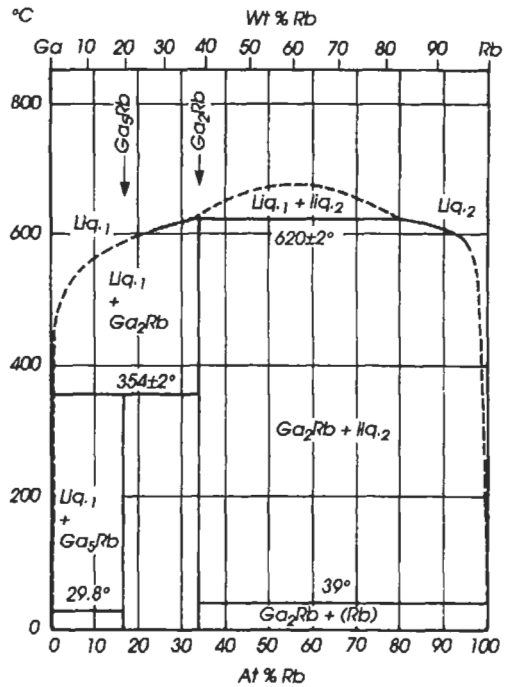
Ga–Pu


Wt.% Pu
°C
10 20 30 40 50 60 70 80 90 95
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
PuGa3
PuGa2
Pu2Ga3
PuGa
Pu5Ga3
Pu3Ga
1264 ± 10°
Liquid
1105 ± 2°
979 ± 7°
922 ± 1°
928 ± 7°
58
767 ± 5°
η
± 4°
719
677 ± 2°
80
655
± 4°
641
1645 ± 5°
815
87 5
α-Pu
δ-Pu
δ'-Pu
363 ± 10°
γ-Pu
β-Pu
α-Pu
29·8°
0 10 20 30 40 50 60 70 80 90 100
At.% Pu

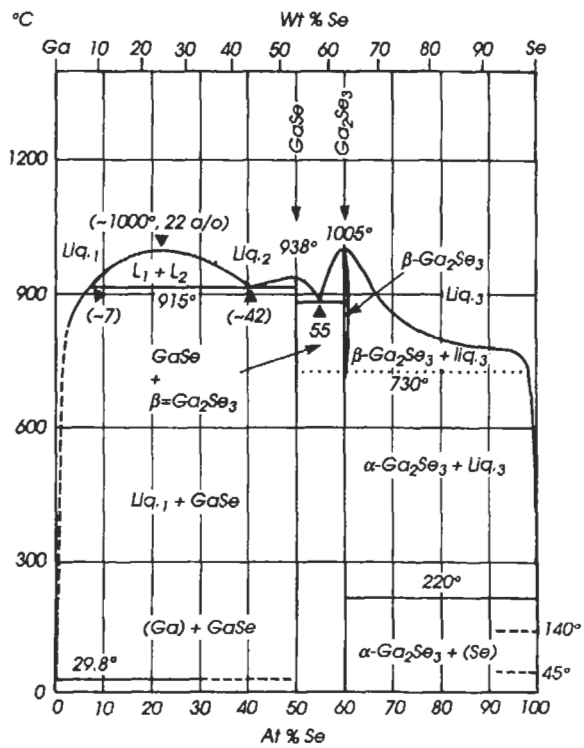
Ga–Sb


Wt.% Ga
°C
10 20 30 40 50 60 70 80 90
800
700
600
500
400
300
200
100
705·9°
Liquid
589·8°
GaSb
29·8°
0 10 20 30 40 50 60 70 80 90 100
At.% Ga

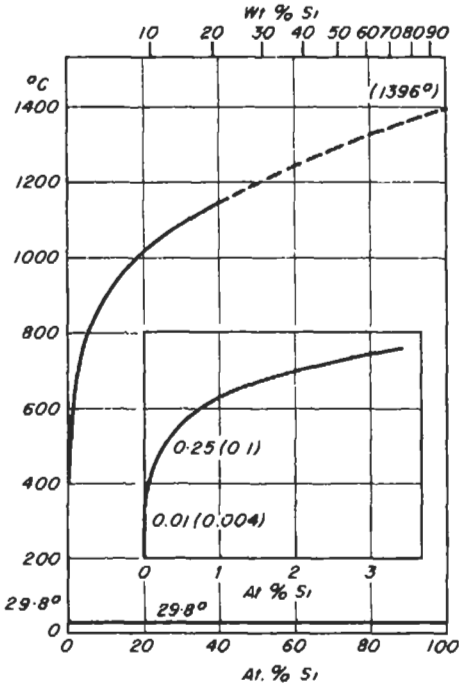
Ga–Rb


°C
Wt % Rb
Ga 10 20 30 40 50 60 70 80 90 Rb
800
600
400
200
0
Ga_5Rb
Ga_2Rb
Liq.1
Liq.1 + liq.2
Liq.2
620±2°
Liq.1 + Ga_2Rb
354±2°
Ga_2Rb + liq.2
Liq.1 + Ga_5Rb
29.8°
39°
Ga_2Rb + (Rb)
0 10 20 30 40 50 60 70 80 90 100
At % Rb

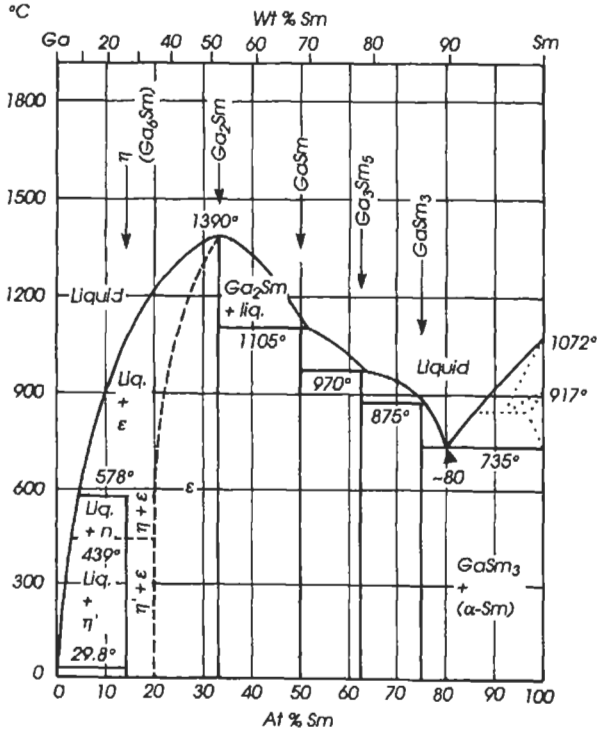
Ga–Se


°C
Wt % Se
Ga 10 20 30 40 50 60 70 80 90 Se
1200
900
600
300
0
GaSe
Ga_2Se_3
(~1000°, 22 a/o)
Liq.1
$L_1 + L_2$
Liq.2
938°
1005°
β-Ga_2Se_3
915°
Liq.3
(~7)
(~42)
55
GaSe + β=Ga_2Se_3
β-Ga_2Se_3 + liq.3
730°
α-Ga_2Se_3 + Liq.3
Liq.1 + GaSe
220°
(Ga) + GaSe
140°
29.8°
α-Ga_2Se_3 + (Se)
45°
0 10 20 30 40 50 60 70 80 90 100
At % Se

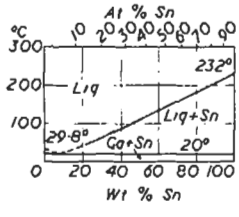
Ga–Si



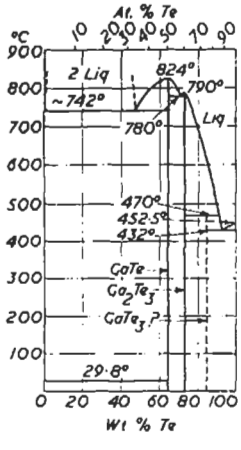
Ga–Sm



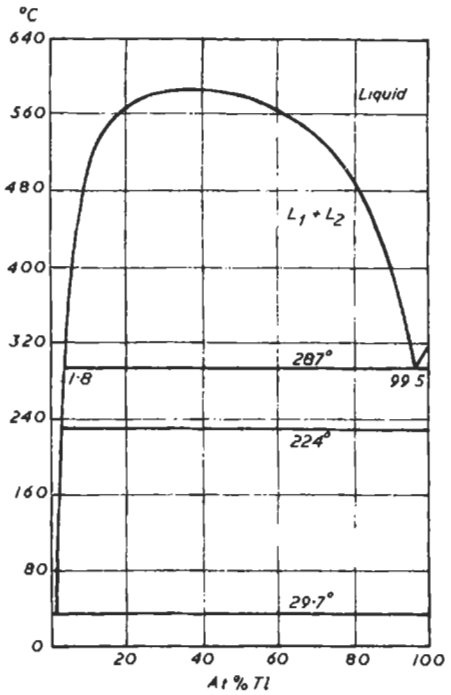
Ga–Sn



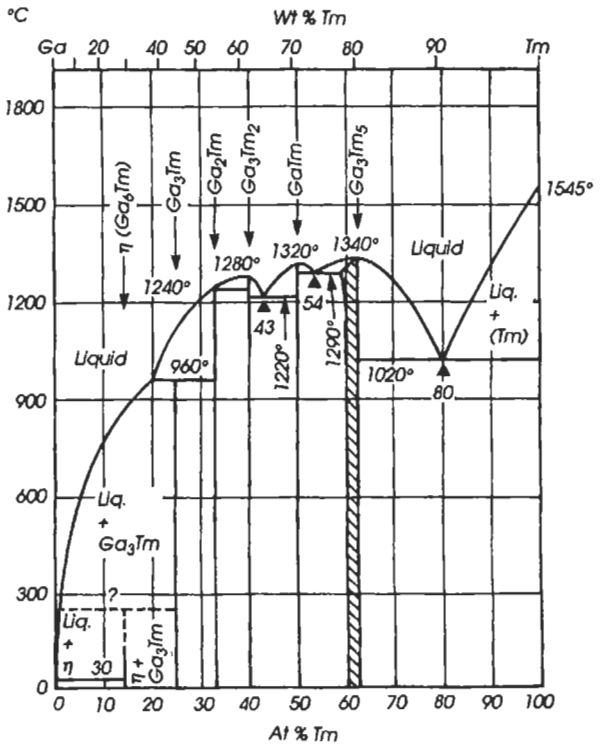
Ga–Te



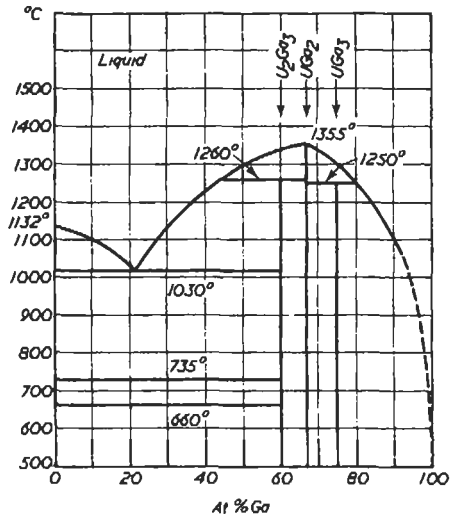
Ga–Tl


°C
640
560
480
400
320
240
160
80
0
Liquid
$L_1 + L_2$
287°
1·8
99·5
224°
29·7°
20
40
60
80
100
At % Tl

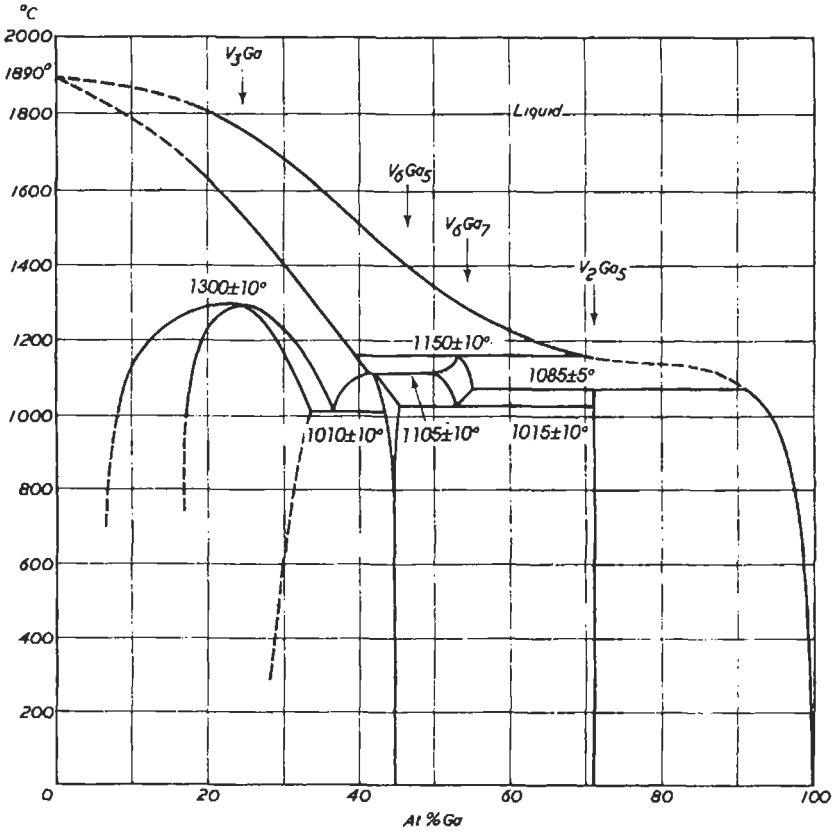
Ga–Tm


°C
Wt % Tm
Ga
20
40
50
60
70
80
90
Tm
1800
1500
1200
900
600
300
0
η (Ga_6Tm)
Ga_3Tm
Ga_2Tm
Ga_3Tm_2
GaTm
Ga_3Tm_5
1545°
1240°
1280°
1320°
1340°
Liquid
Liq. + (Tm)
960°
43
1220°
54
1290°
1020°
80
Liquid
Liq. + Ga_3Tm
?
Liq. + η
30
η + Ga_3Tm
0
10
20
30
40
50
60
70
80
90
100
At % Tm

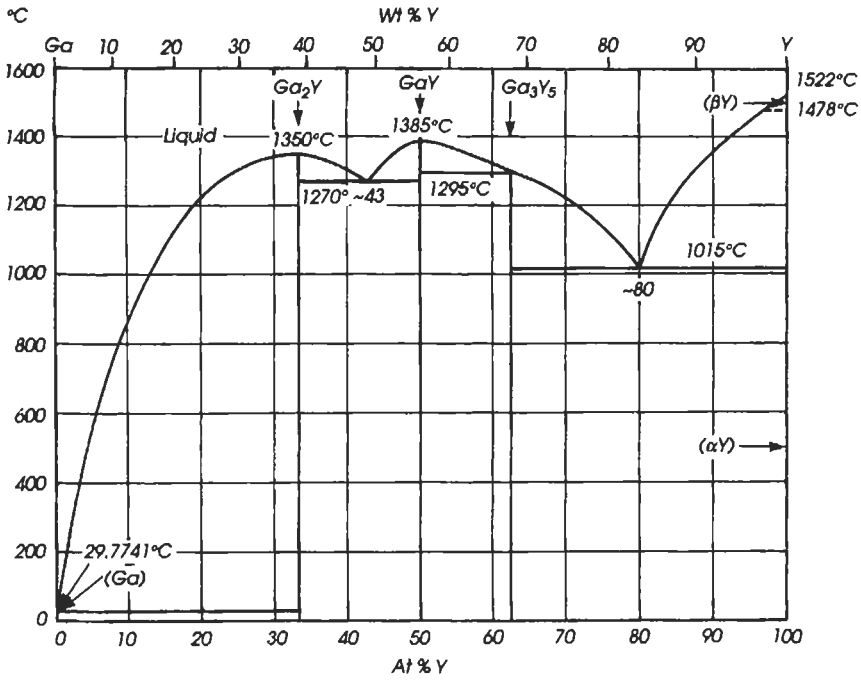
Ga–U


°C
Liquid
U3Ga5
UGa2
UGa3
1500
1400
1300
1200
1132°
1100
1000
900
800
700
600
500
1355°
1260°
1250°
1030°
735°
660°
0
20
40
60
80
100
At % Ga

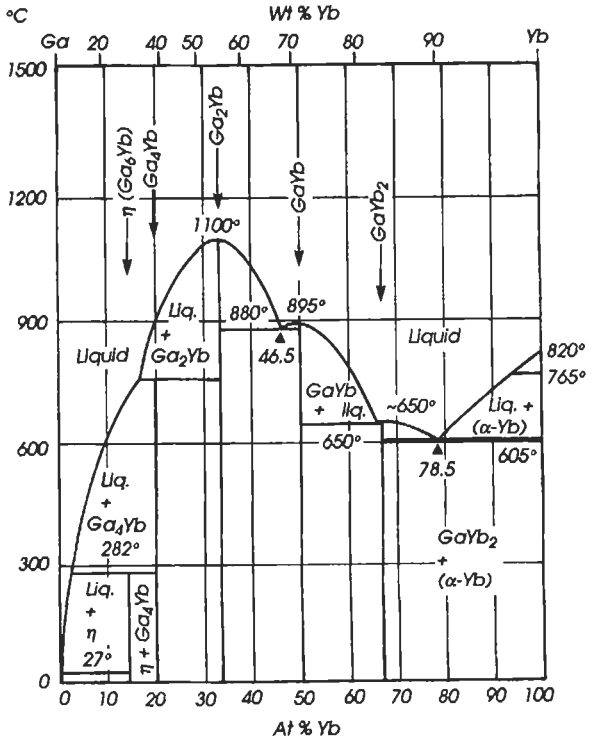
Ga–V


°C
2000
1890°
1800
1600
1400
1200
1000
800
600
400
200
V3Ga
Liquid
V6Ga5
V6Ga7
V2Ga5
1300±10°
1150±10°
1085±5°
1010±10°
1105±10°
1015±10°
0
20
40
60
80
100
At % Ga

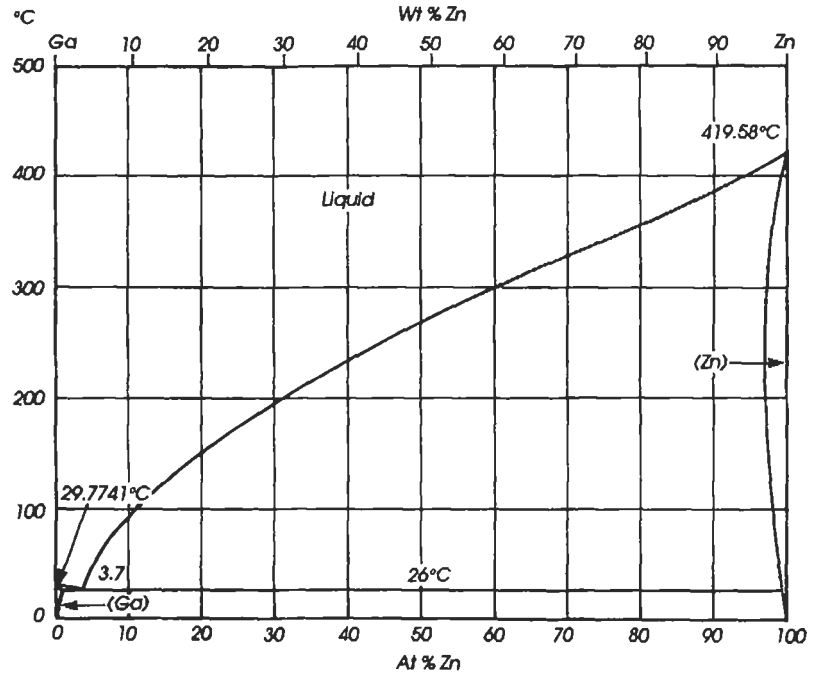
Ga–Y


°C
Wt % Y
Ga
Y
Ga_2Y
GaY
Ga_3Y_5
Liquid
1350°C
1385°C
1270°
~43
1295°C
1522°C
1478°C
(βY)
1015°C
~80
(αY)
29.7741°C
(Ga)
At % Y

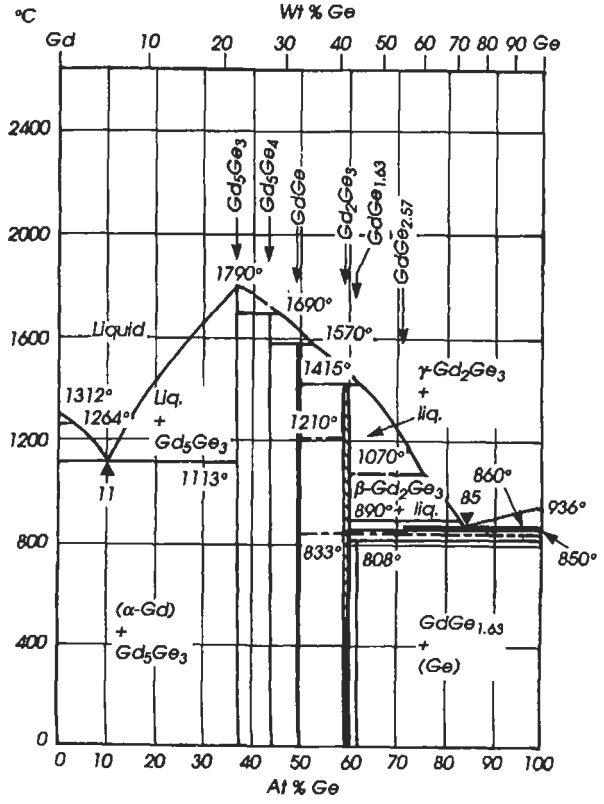
Ga–Yb


°C
Wt % Yb
Ga
Yb
η (Ga6Yb)
Ga4Yb
Ga2Yb
GaYb
GaYb2
1100°
Liq. + Ga2Yb
880°
895°
Liquid
46.5
Liquid
820°
765°
GaYb + liq.
~650°
Liq. + (α-Yb)
650°
605°
78.5
Liq. + Ga4Yb 282°
GaYb2 + (α-Yb)
Liq. + η 27°
η + Ga4Yb
At % Yb

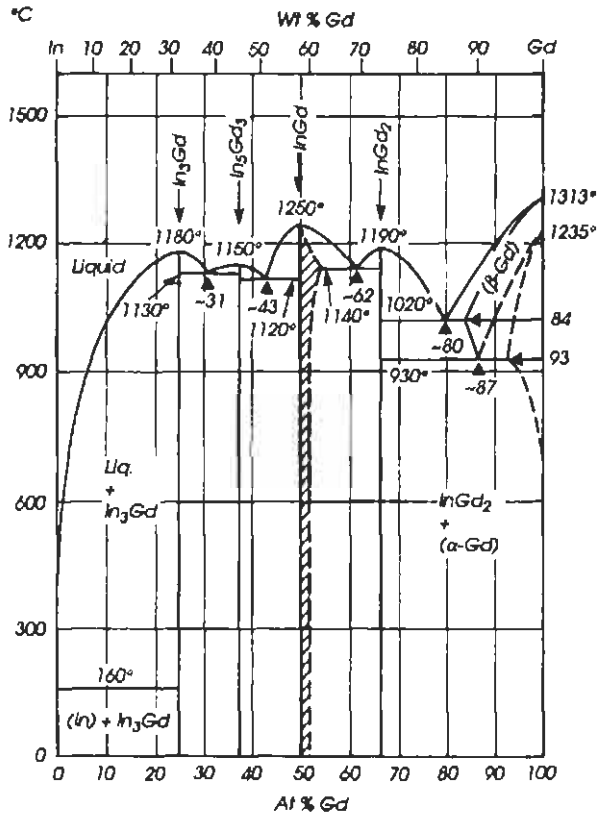
Ga–Zn


°C
Wt % Zn
Ga 10 20 30 40 50 60 70 80 90 Zn
500
400
300
200
100
0
419.58°C
Liquid
(Zn)
29.7741°C
3.7
26°C
(Ga)
0 10 20 30 40 50 60 70 80 90 100
At % Zn

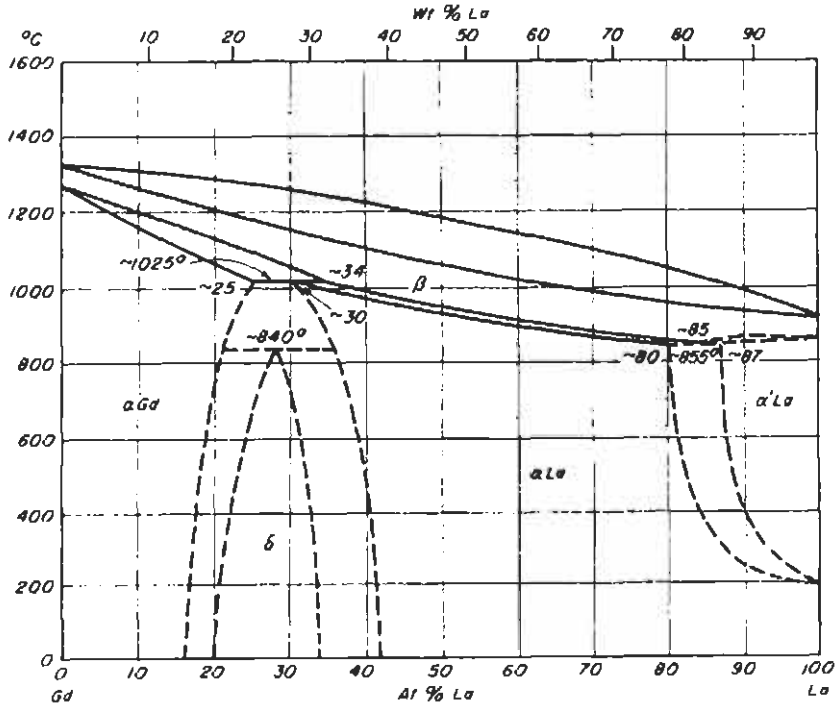
Gd–Ge


°C
Wt % Ge
Gd 10 20 30 40 50 60 70 80 90 Ge
2400
2000
1600
1200
800
400
0
Gd_5Ge_3
Gd_5Ge_4
GdGe
Gd_2Ge_3
$GdGe_{1.63}$
$GdGe_{2.57}$
1790°
1690°
1570°
Liquid
1415°
γ-Gd_2Ge_3
+
liq.
1312°
1264°
Liq.
+
Gd_5Ge_3
1210°
1070°
1113°
11
β-Gd_2Ge_3
890° + liq.
860°
85
936°
833°
808°
850°
(α-Gd)
+
Gd_5Ge_3
$GdGe_{1.63}$
+
(Ge)
0 10 20 30 40 50 60 70 80 90 100
At % Ge

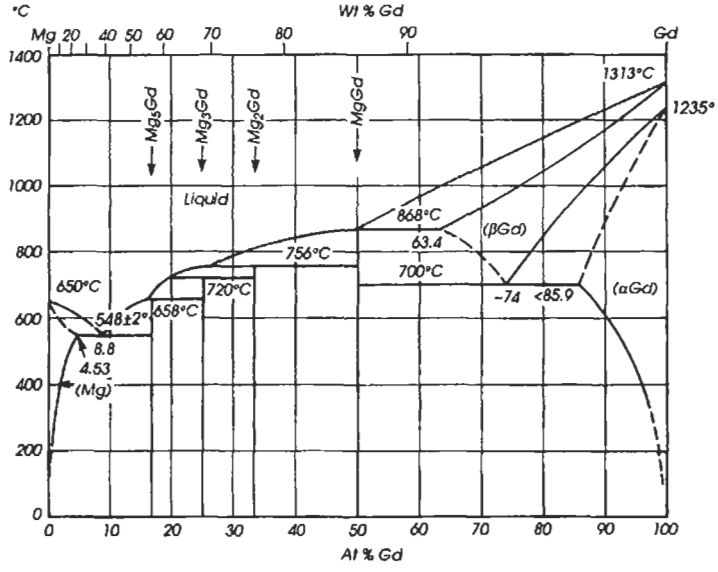
Gd–In


°C
Wt % Gd
In
Gd
Liquid
In_3Gd
In_5Gd_3
InGd
$InGd_2$
1313°
1235°
1250°
1180°
1150°
1190°
1130°
~31
~43
1120°
~62
1140°
1020°
~80
84
93
930°
~87
(β-Gd)
Liq. + In_3Gd
$InGd_2$ + (α-Gd)
160°
(In) + In_3Gd
At % Gd

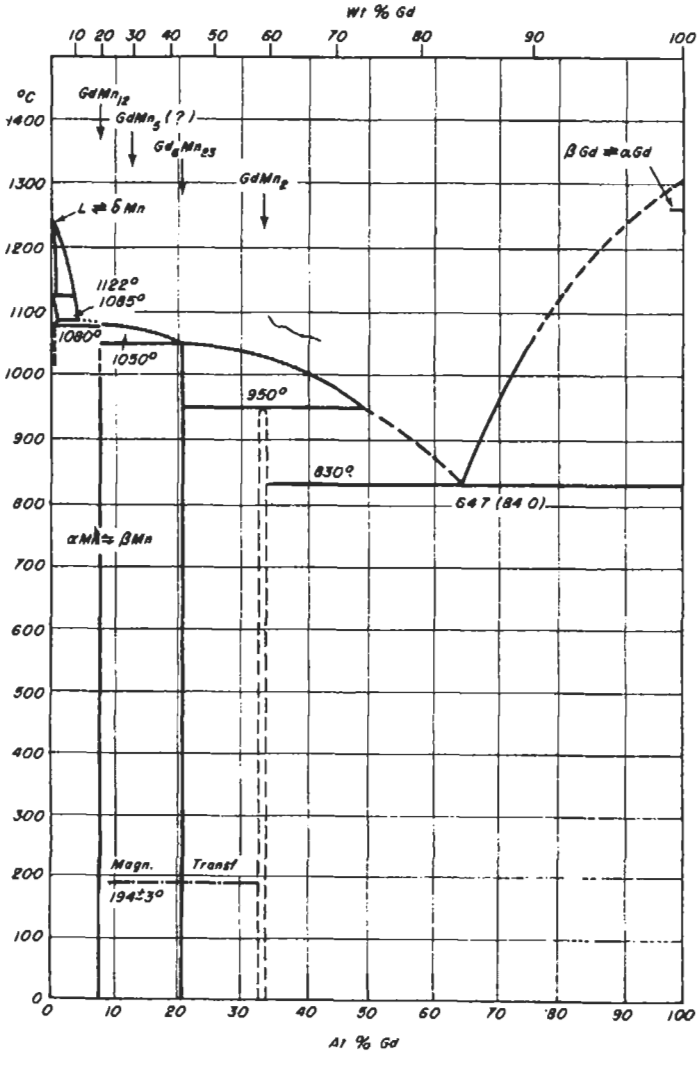
Gd–La


°C
Wt % La
~1025°
~25
~34
β
~30
~840°
~85
~80
~855°
~87
αGd
α'La
αLa
δ
Gd
At % La
La

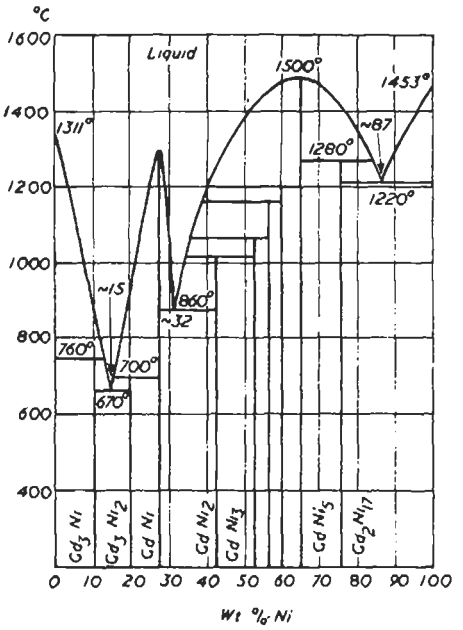
Gd–Mg


°C
Wt % Gd
Mg 20 40 50 60 70 80 90 Gd
1400
1200
1000
800
600
400
200
0
Mg5Gd
Mg3Gd
Mg2Gd
MgGd
Liquid
1313°C
1235°
868°C
(βGd)
63.4
756°C
700°C
650°C
720°C
658°C
548±2°
8.8
4.53
(Mg)
-74
<85.9
(αGd)
0 10 20 30 40 50 60 70 80 90 100
At % Gd

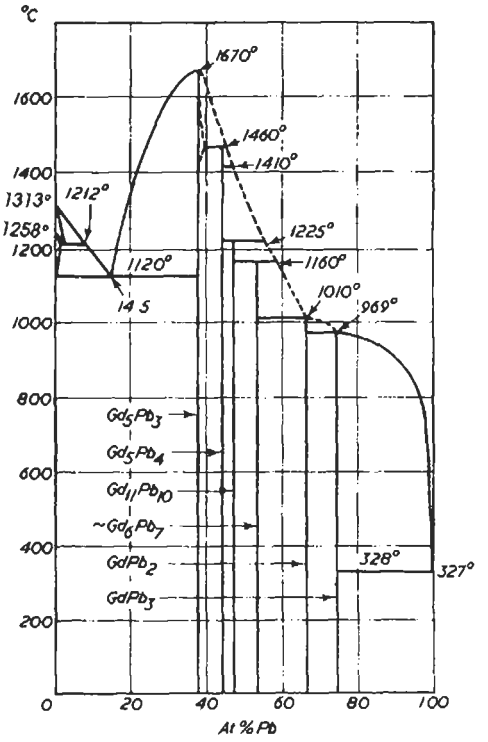
Gd–Mn


Wt % Gd
10 20 30 40 50 60 70 80 90 100
°C
GdMn12
GdMn5 (?)
Gd6Mn23
GdMn2
L ⇌ δ Mn
1122°
1085°
1080°
1050°
950°
830°
647 (84 0)
β Gd ⇌ α Gd
αMn ⇌ βMn
Magn. Transf
194±3°
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
0 10 20 30 40 50 60 70 80 90 100
At % Gd

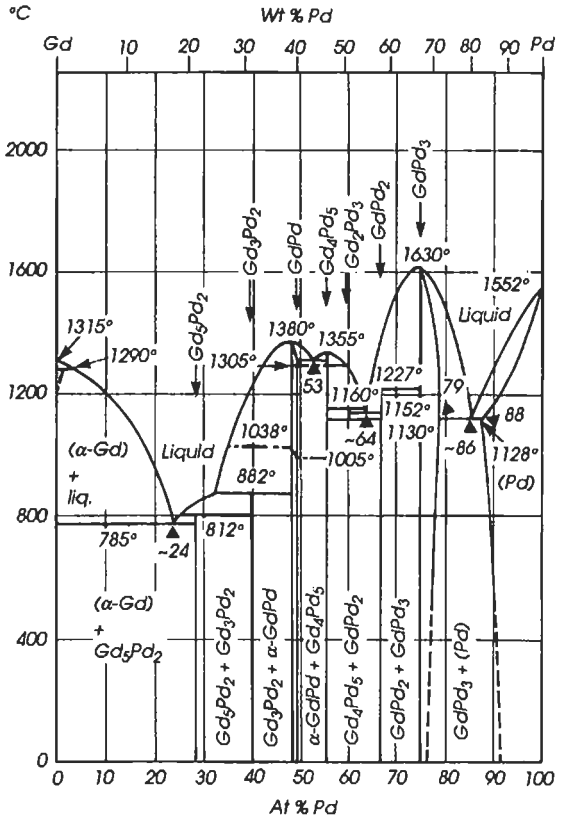
Gd–Ni


°C
1600
1400
1200
1000
800
600
400
Liquid
1500°
1453°
1311°
~87
1280°
1220°
~15
860°
~32
760°
700°
670°
Gd3 Ni
Gd5 Ni2
Gd Ni
Gd Ni2
Gd Ni3
Gd Ni5
Gd2 Ni17
0 10 20 30 40 50 60 70 80 90 100
Wt % Ni

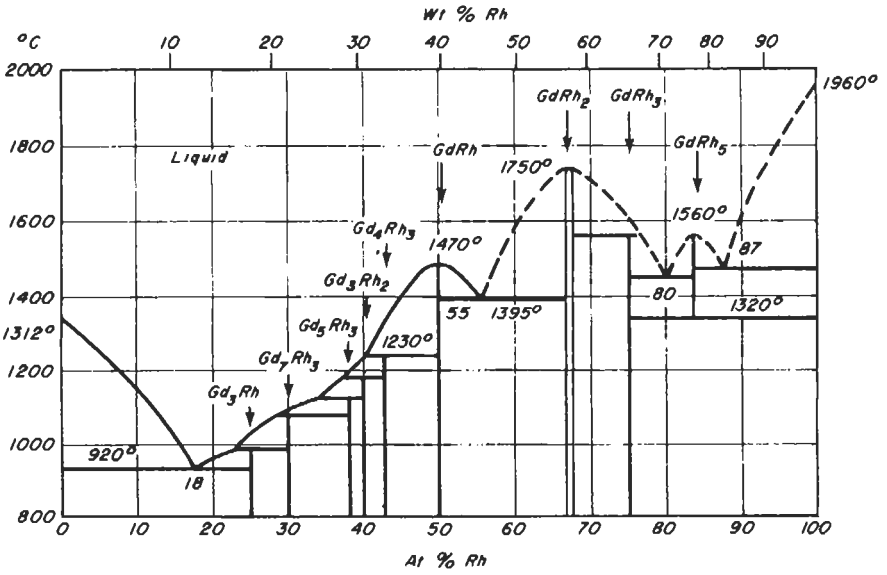
Gd–Pb


°C
1600
1400
1313°
1258°
1200
1000
800
600
400
200
1670°
1460°
1410°
1212°
1225°
1160°
1120°
14 S
1010°
969°
Gd5Pb3
Gd5Pb4
Gd11Pb10
~Gd6Pb7
GdPb2
GdPb3
328°
327°
0 20 40 60 80 100
At % Pb

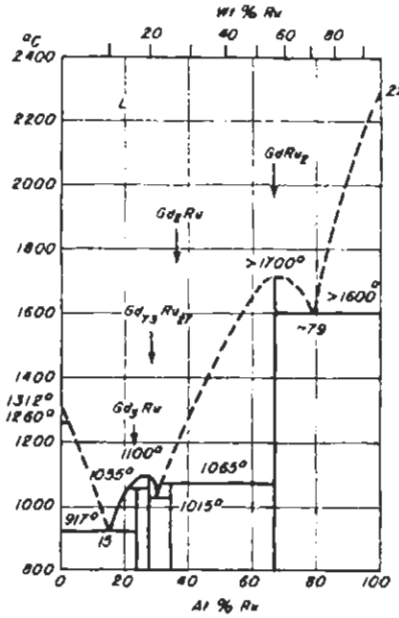
Gd–Pd


°C
Wt % Pd
Gd
Pd
At % Pd
Liquid
(α-Gd) + liq.
(α-Gd) + Gd5Pd2
Gd5Pd2 + Gd3Pd2
Gd3Pd2 + α-GdPd
α-GdPd + Gd4Pd5
Gd4Pd5 + GdPd2
GdPd2 + GdPd3
GdPd3 + (Pd)
1315°
1290°
1305°
1380°
1355°
1160°
1227°
1152°
1130°
1630°
1552°
1038°
1005°
882°
785°
812°
1128°
(Pd)
53
~64
79
~86
88
~24

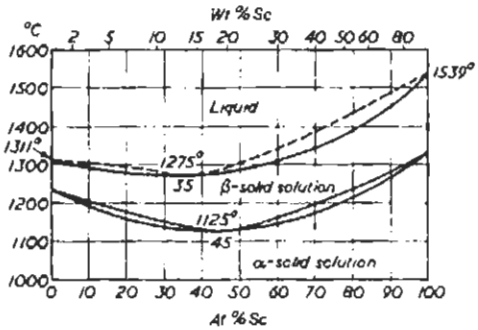
Gd–Rh


Wt % Rh
°C
At % Rh
Liquid
GdRh
GdRh2
GdRh3
GdRh5
Gd4Rh3
Gd3Rh2
Gd5Rh3
Gd7Rh3
Gd3Rh
1960°
1750°
1560°
1470°
1395°
1320°
1312°
1230°
920°
18
55
80
87

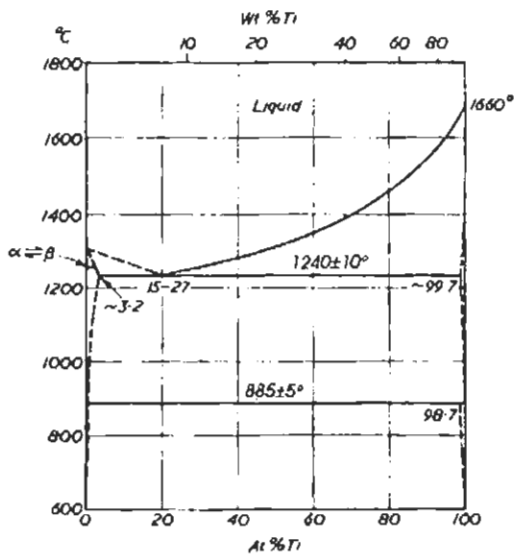
Gd–Ru



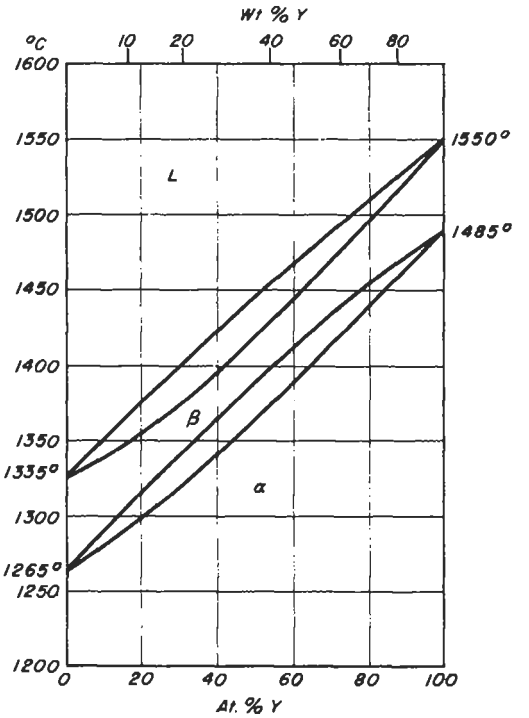
Gd–Sc



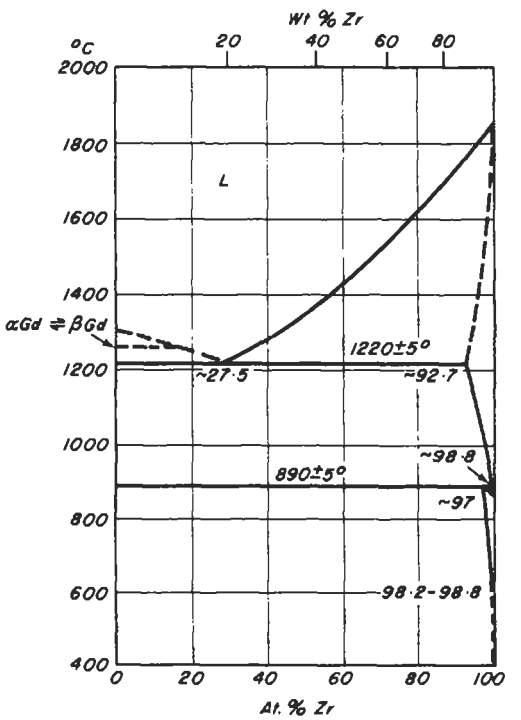
Gd–Ti



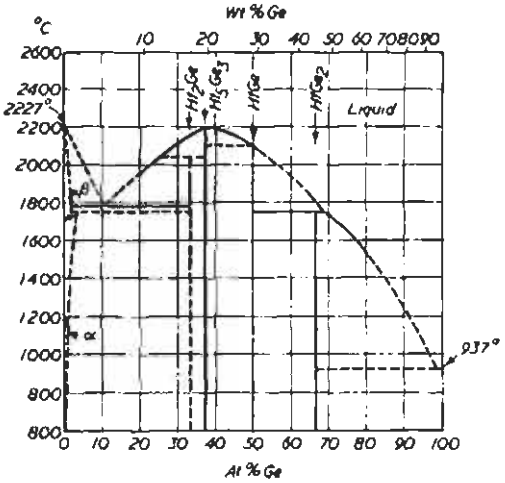
Gd–Y


Wt % Y
°C
10
20
40
60
80
1600
1550
1500
1450
1400
1350
1335°
1300
1265°
1250
1200
1550°
1485°
L
β
α
0
20
40
60
80
100
At. % Y

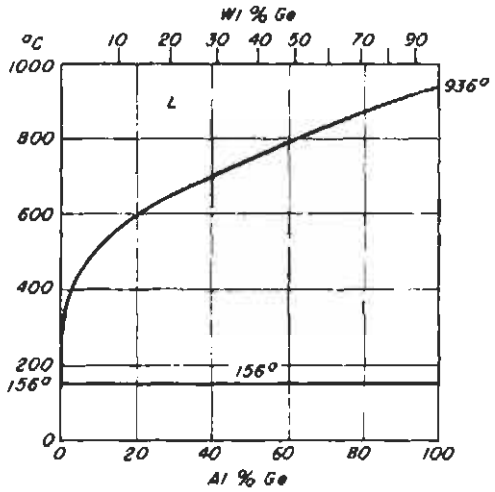
Gd–Zr


Wt % Zr
°C
20
40
60
80
2000
1800
1600
1400
1200
1000
800
600
400
αGd ⇌ βGd
~27·5
1220±5°
~92·7
~98·8
890±5°
~97
98·2-98·8
L
0
20
40
60
80
100
At. % Zr

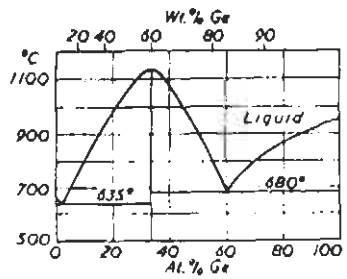
Ge–Hf



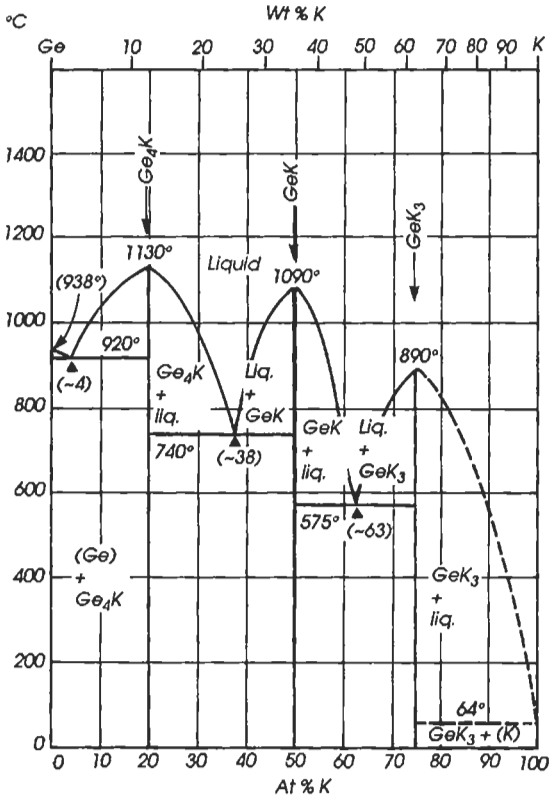
Ge–In



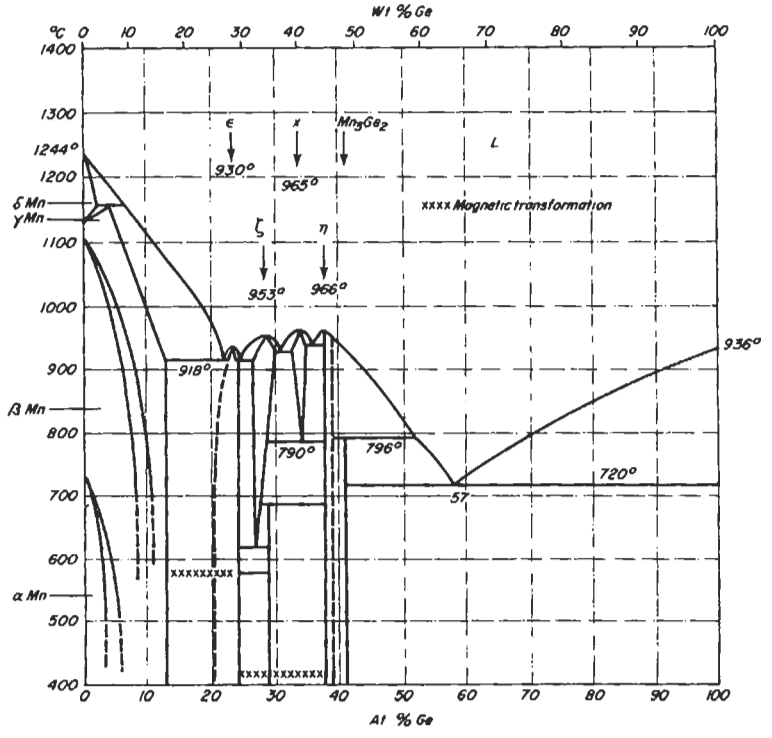
Ge–Mg



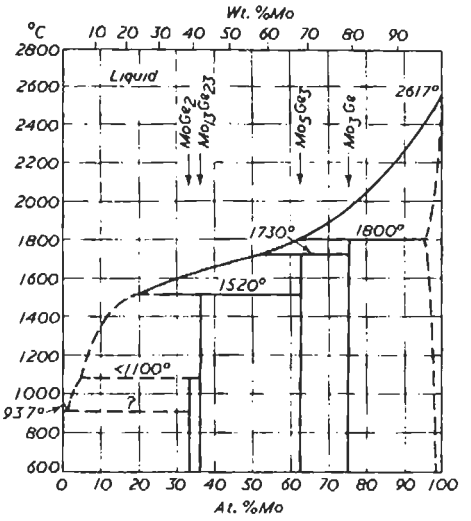
Ge–K


°C
Wt % K
Ge
K
Ge_4K
GeK
GeK_3
1130°
Liquid
1090°
(938°)
920°
(~4)
Ge_4K + liq.
Liq. + GeK
740°
(~38)
GeK + liq.
Liq. + GeK_3
890°
575°
(~63)
(Ge) + Ge_4K
GeK_3 + liq.
64°
GeK_3 + (K)
At % K

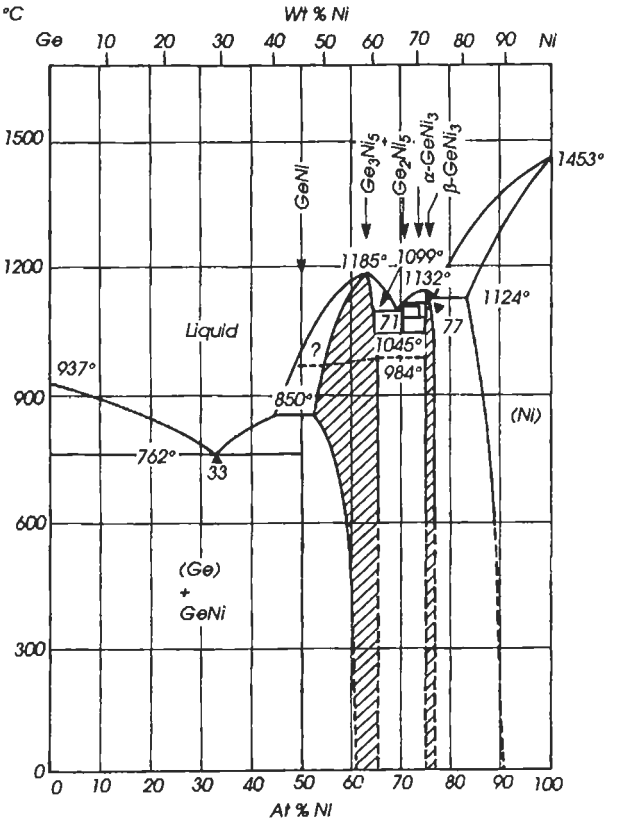
Ge–Mn


Wt % Ge
°C
ε
χ
Mn_3Ge_2
L
1244°
930°
965°
δ Mn
γ Mn
xxxx Magnetic transformation
ζ
η
953°
966°
936°
918°
β Mn
790°
796°
720°
57
α Mn
At % Ge

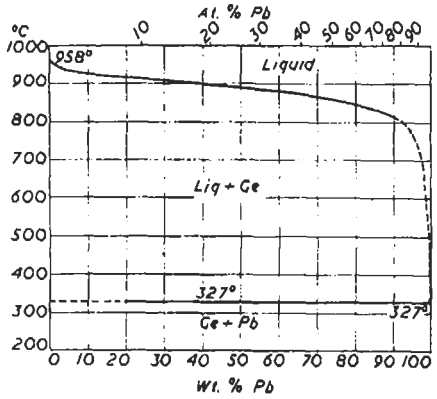
Ge–Mo


Wt. %Mo
°C
10 20 30 40 50 60 70 80 90
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
Liquid
MoGe2
Mo13Ge23
Mo5Ge3
Mo3Ge
2617°
1730°
1800°
1520°
<1100°
937°
?
0 10 20 30 40 50 60 70 80 90 100
At. %Mo

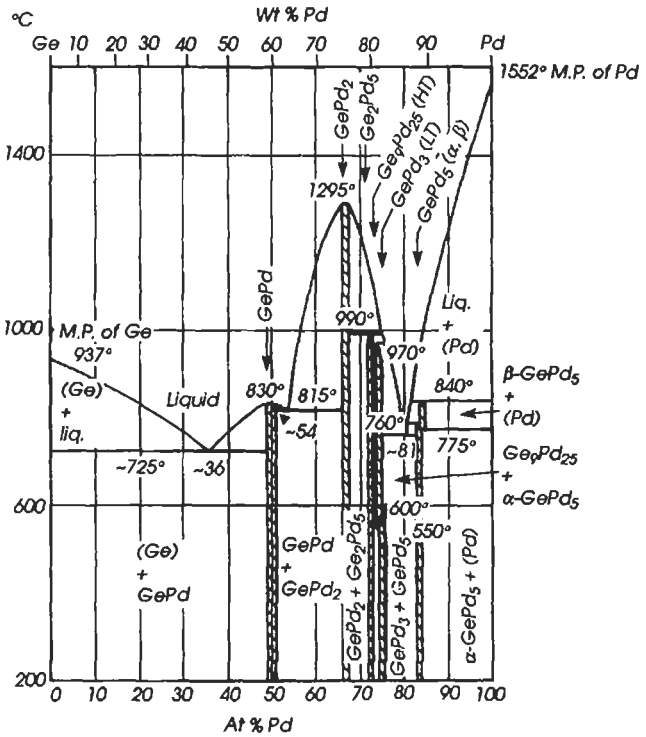
Ge–Ni


°C
Wt % Ni
Ge 10 20 30 40 50 60 70 80 90 Ni
1500
1200
900
600
300
0
GeNi
Ge3Ni5
Ge2Ni5
α-GeNi3
β-GeNi3
1453°
1185°
1099°
1132°
1124°
71
77
Liquid
?
1045°
984°
937°
850°
762°
33
(Ni)
(Ge)
+
GeNi
0 10 20 30 40 50 60 70 80 90 100
At % Ni

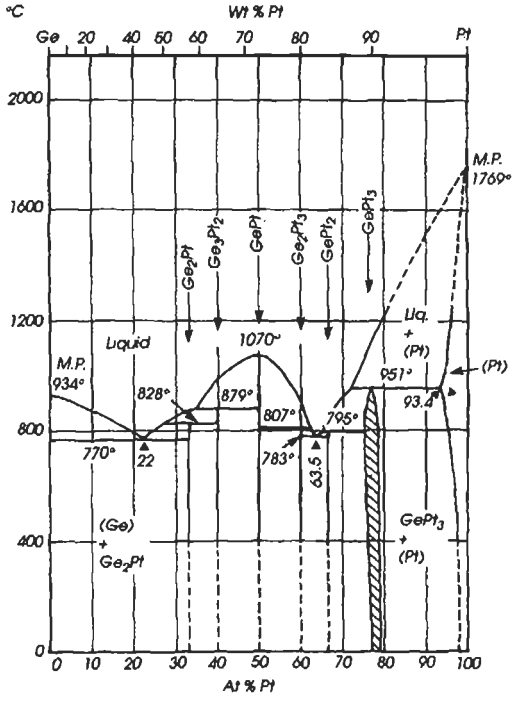
Ge–Pb


°C
At. % Pb
10 20 30 40 50 60 70 80 90
1000
900
800
700
600
500
400
300
200
958°
Liquid
Liq + Ge
327°
Ge + Pb
327°
0 10 20 30 40 50 60 70 80 90 100
Wt. % Pb

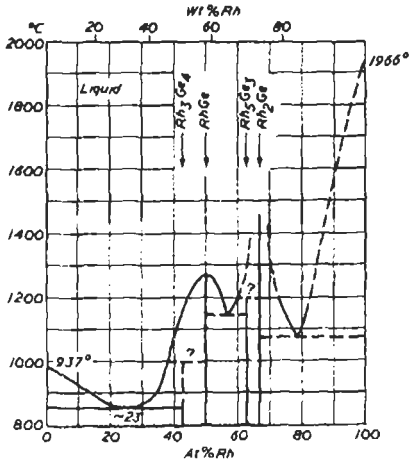
Ge–Pd


°C
Wt % Pd
Ge 10 20 30 40 50 60 70 80 90 Pd
1552° M.P. of Pd
GePd2
Ge2Pd5
Ge9Pd25 (HT)
GePd3 (LT)
GePd5 (α, β)
1400
1295°
GePd
990°
970°
Liq. + (Pd)
1000
M.P. of Ge 937°
(Ge) + liq.
Liquid
830°
815°
~54
760°
~81
840°
β-GePd5 + (Pd)
775°
Ge9Pd25 + α-GePd5
~725°
~36
600
600°
550°
(Ge) + GePd
GePd + GePd2
GePd2 + Ge2Pd5
Ge2Pd5 + GePd3
GePd3 + GePd5
α-GePd5 + (Pd)
200
0 10 20 30 40 50 60 70 80 90 100
At % Pd

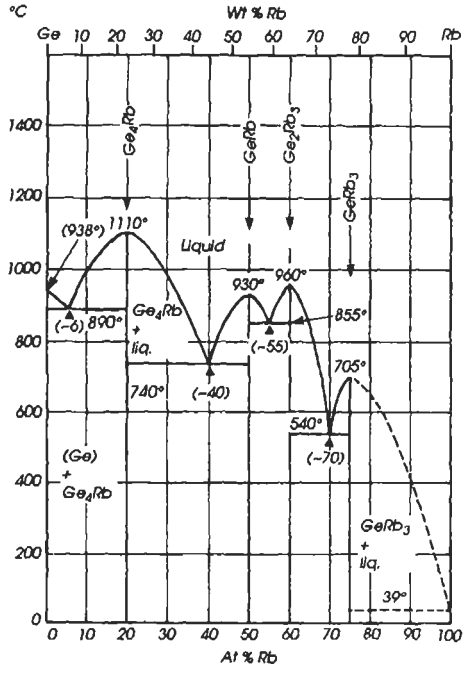
Ge–Pt



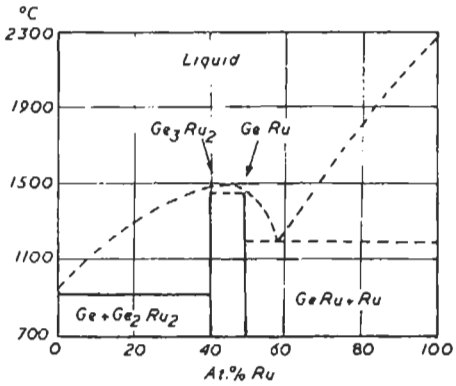
Ge–Rh



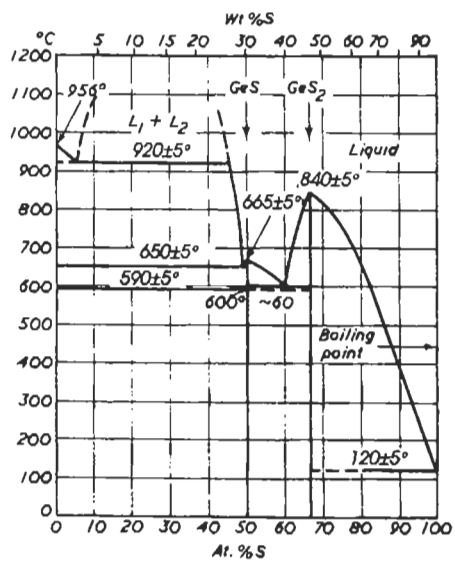
Ge–Rb



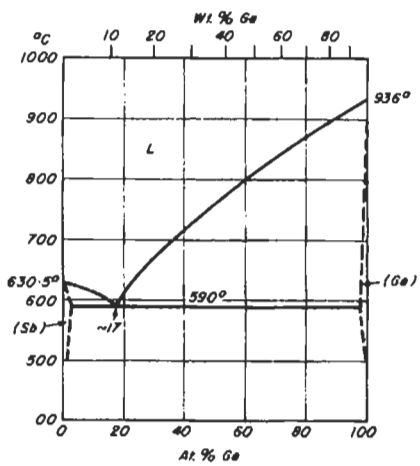
Ge–Ru



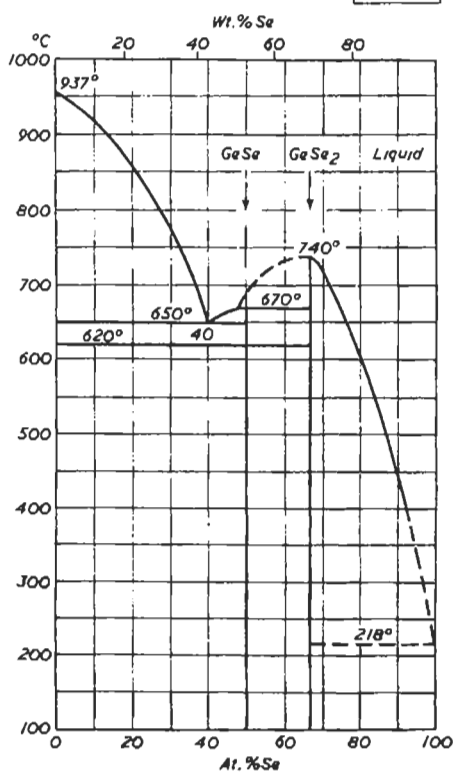
Ge–S

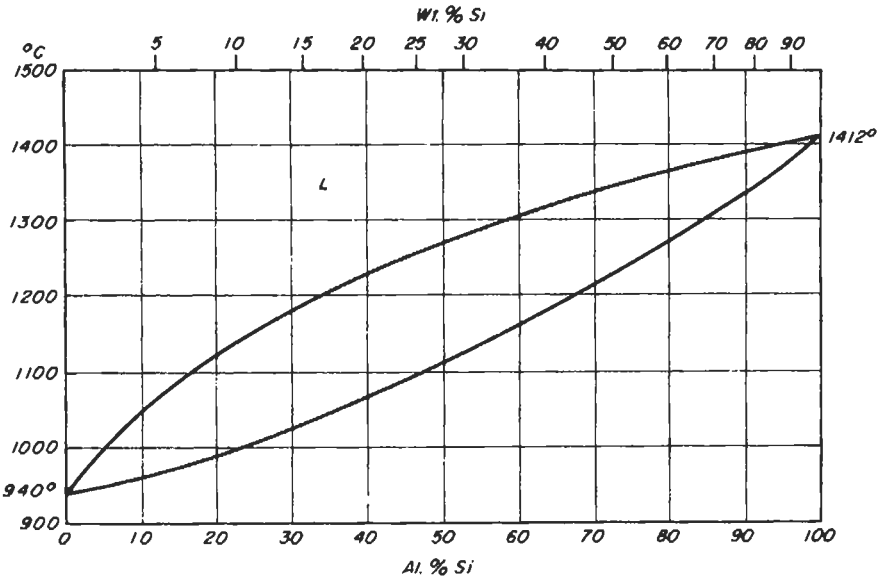


Ge–Sb

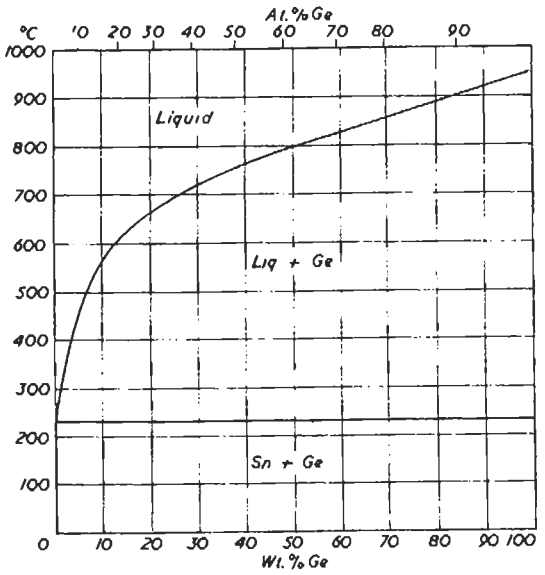


Ge–Se



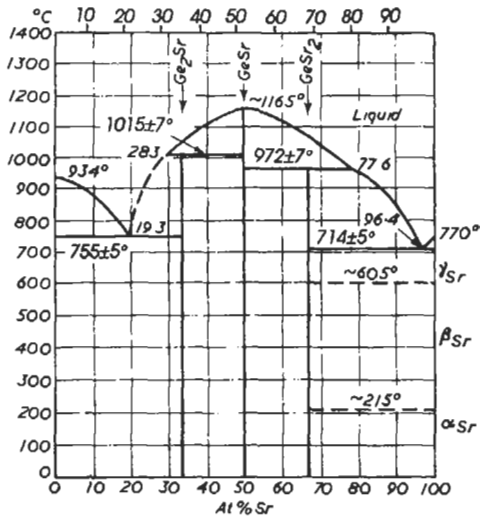

Wt. % Si
°C
5 10 15 20 25 30 40 50 60 70 80 90
1500
1400
1300
1200
1100
1000
940°
900
1412°
L
0 10 20 30 40 50 60 70 80 90 100
At. % Si

Ge–Si

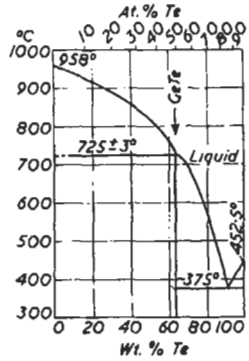

At. % Ge
°C
10 20 30 40 50 60 70 80 90
1000
900
800
700
600
500
400
300
200
100
0
Liquid
Liq + Ge
Sn + Ge
10 20 30 40 50 60 70 80 90 100
Wt. % Ge

Ge–Sn

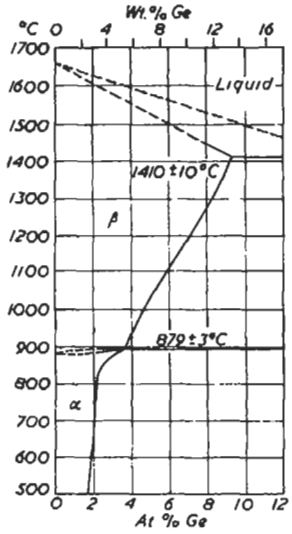
Ge–Sr



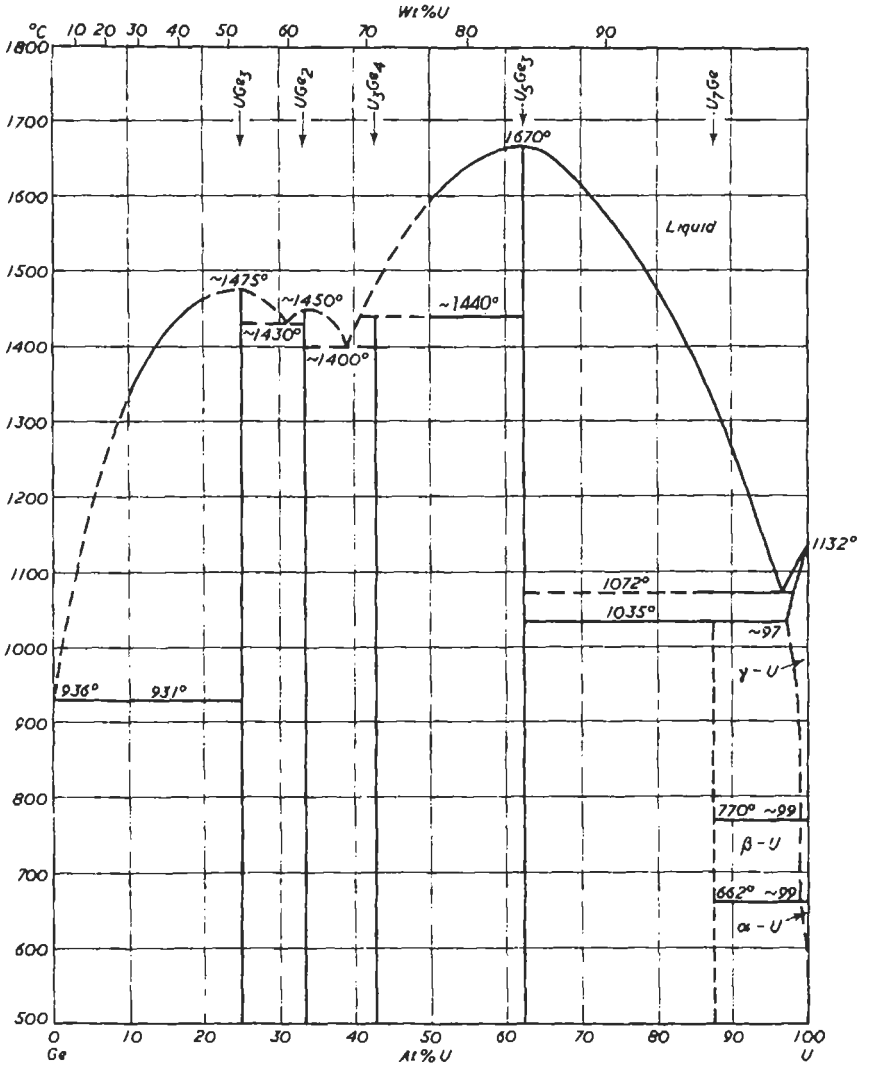
Ge–Te



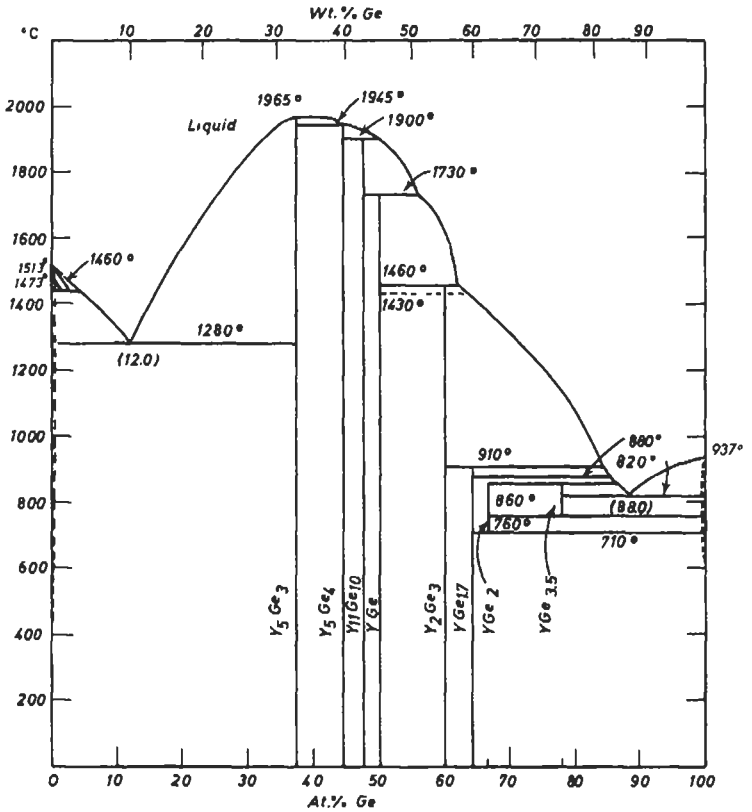
Ge–Ti



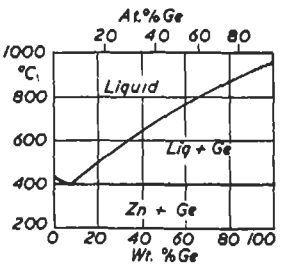
Ge–U

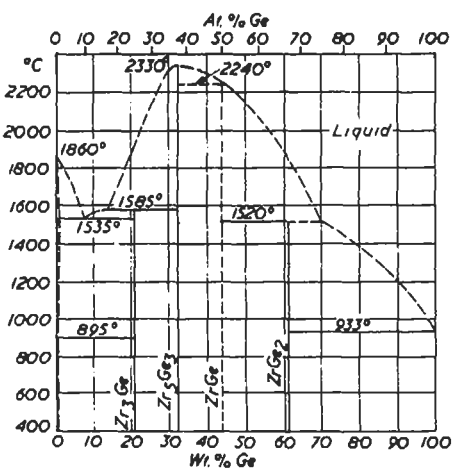

Wt%U
°C
10 20 30 40 50 60 70 80 90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
UGe3
UGe2
U3Ge4
U5Ge3
U7Ge
1670°
Liquid
~1475°
~1450°
~1430°
~1400°
~1440°
1132°
1072°
1035°
~97
γ - U
936°
931°
770° ~99
β - U
662° ~99
α - U
0 10 20 30 40 50 60 70 80 90 100
Ge
At% U
U

Ge–Y



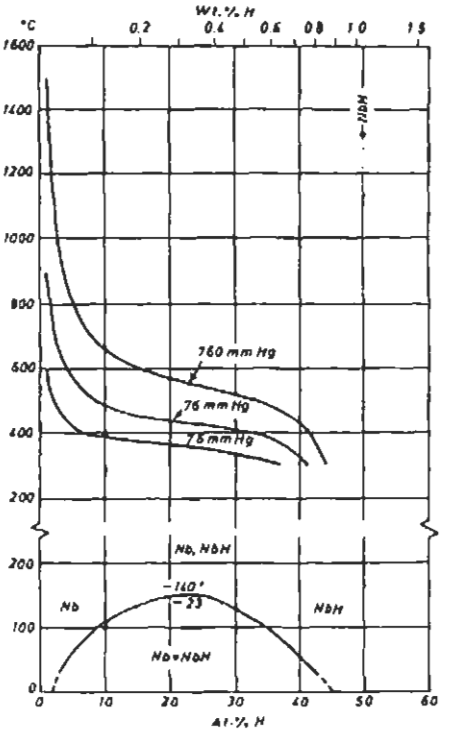
Ge–Zn



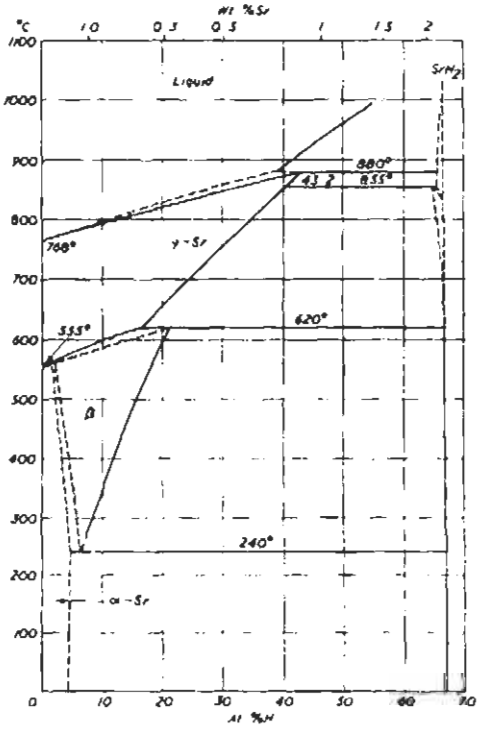


Ge–Zr

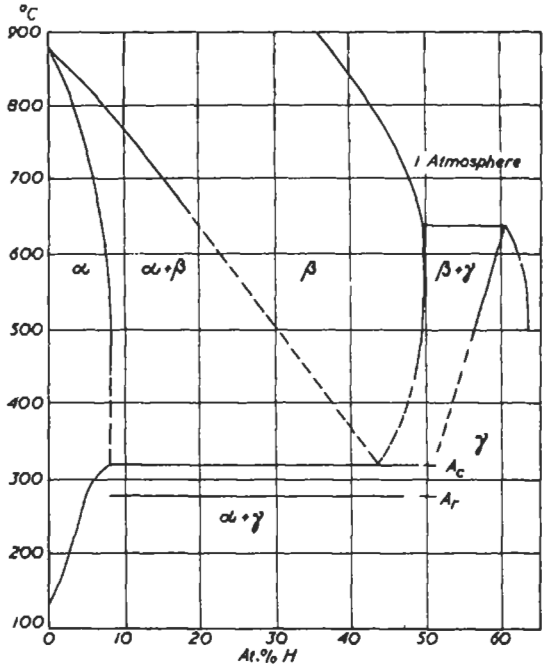
H–Nb


°C
Wt.% H
NbH
760 mm Hg
76 mm Hg
7.5 mm Hg
Nb, NbH
−140°
−53
Nb
NbH
Nb+NbH
At.% H

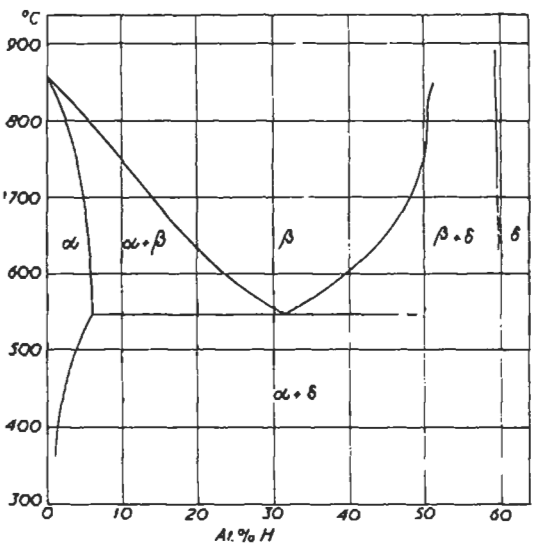
H–Sr


°C
Wt %Sr
Liquid
SrH2
880°
855°
43.2
768°
γ-Sr
620°
555°
240°
α-Sr
At %H

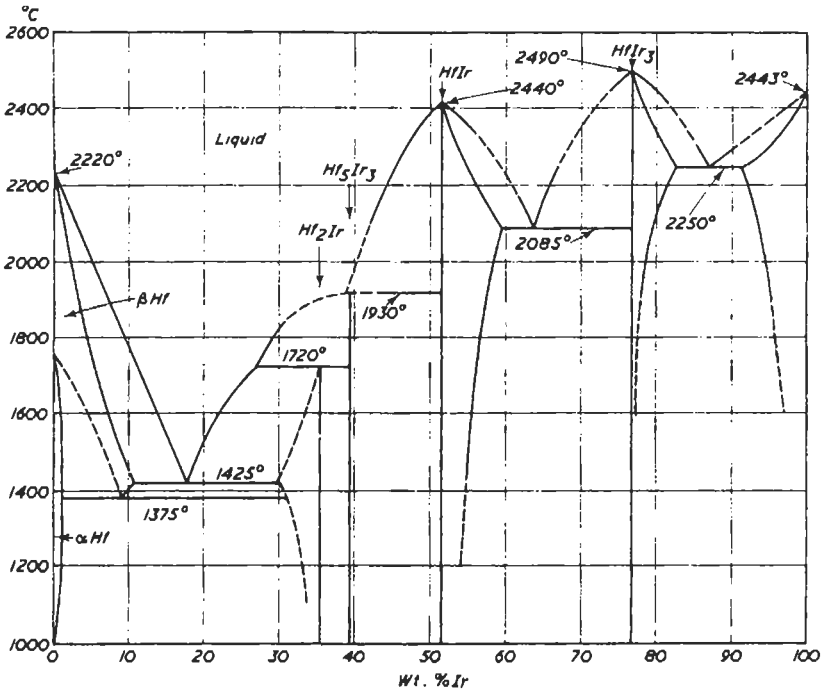
H–Ti


°C
900
800
700
600
500
400
300
200
100
0
10
20
30
40
50
60
At.% H
1 Atmosphere
α
α+β
β
β+γ
γ
A_c
A_r
α+γ

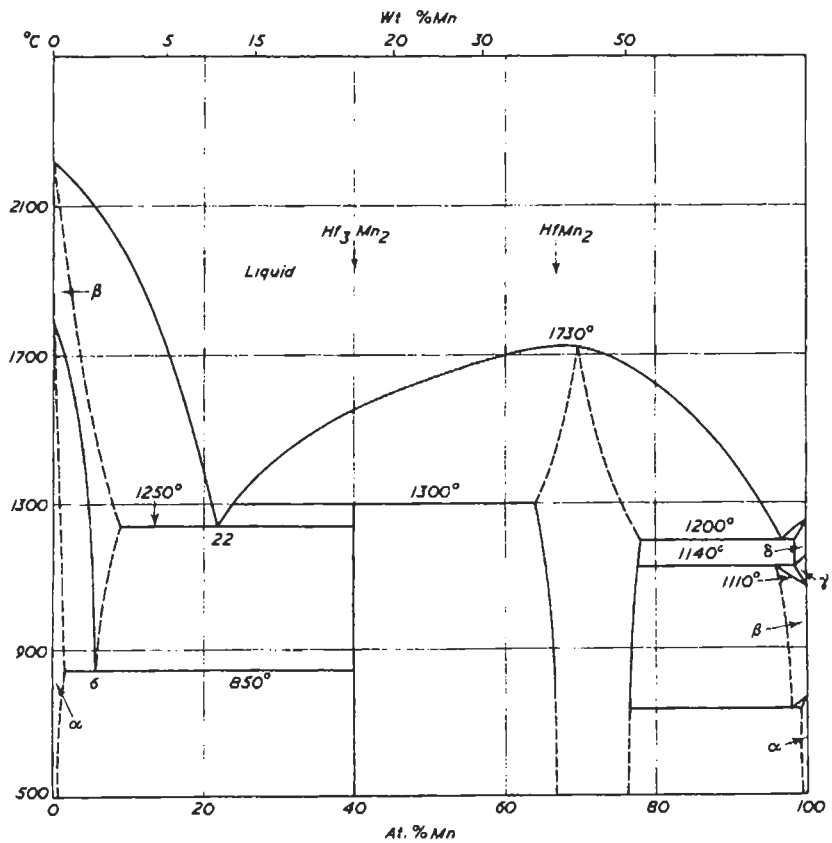
H–Zr


°C
900
800
700
600
500
400
300
0
10
20
30
40
50
60
At.% H
α
α+β
β
β+δ
δ
α+δ

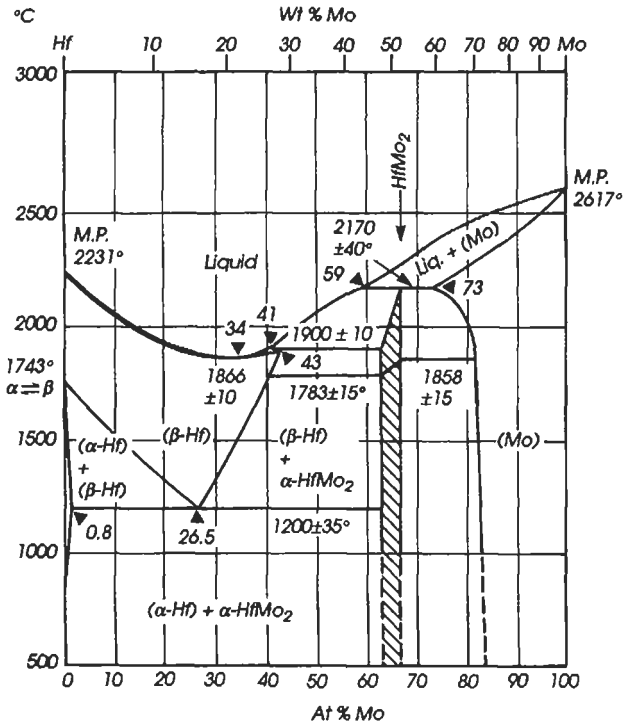
Hf–Ir


°C
2600
2400
2200
2000
1800
1600
1400
1200
1000
Liquid
2220°
βHf
αHf
1425°
1375°
Hf5Ir3
Hf2Ir
1720°
1930°
HfIr
2490°
2440°
HfIr3
2443°
2085°
2250°
0
10
20
30
40
50
60
70
80
90
100
Wt. %Ir

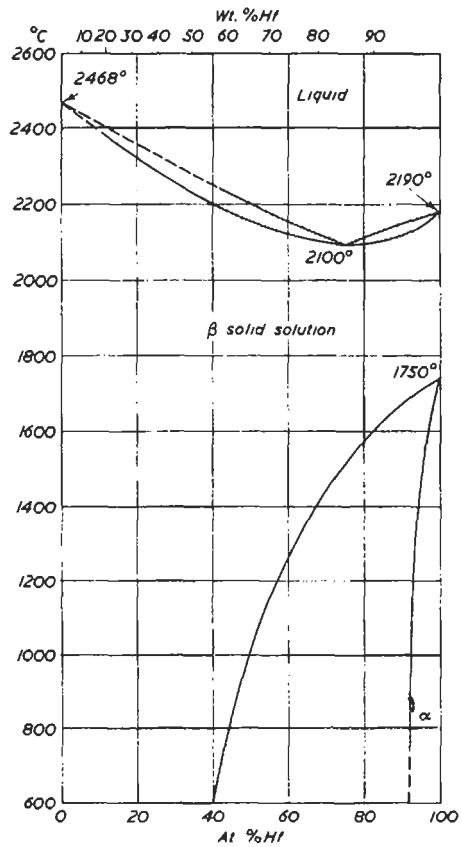
Hf–Mn


Wt %Mn
°C
0
5
15
20
30
50
2100
1700
1300
900
500
Hf3Mn2
HfMn2
Liquid
β
1730°
1250°
1300°
22
1200°
1140°
δ
γ
1110°
β
6
850°
α
α
0
20
40
60
80
100
At. %Mn

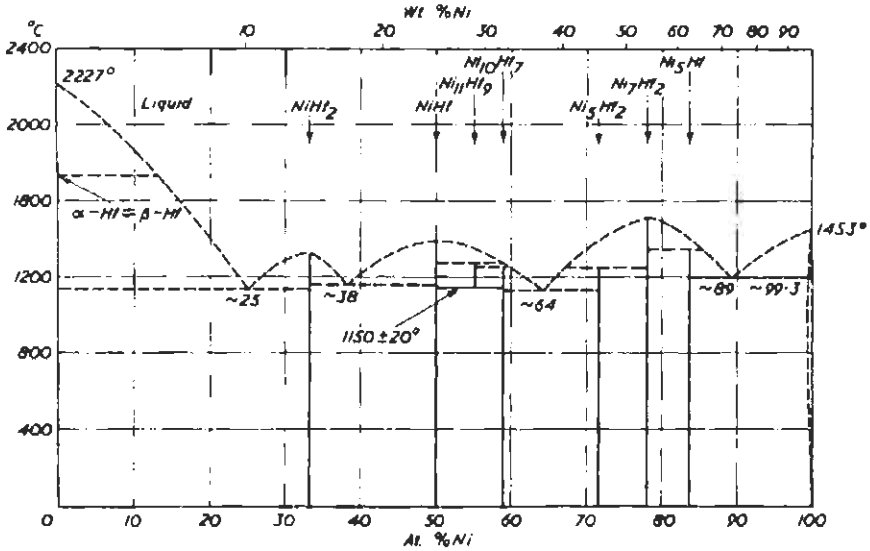
Hf–Mo


°C
Wt % Mo
Hf 10 20 30 40 50 60 70 80 90 Mo
3000
2500
2000
1500
1000
500
HfMo2
M.P. 2617°
M.P. 2231°
Liquid
2170 ±40°
59
Liq. + (Mo)
73
41
34
1900 ± 10
43
1743° α⇌β
1866 ±10
1783±15°
1858 ±15
(α-Hf) + (β-Hf)
(β-Hf) + α-HfMo2
(Mo)
0.8
26.5
1200±35°
(α-Hf) + α-HfMo2
0 10 20 30 40 50 60 70 80 90 100
At % Mo

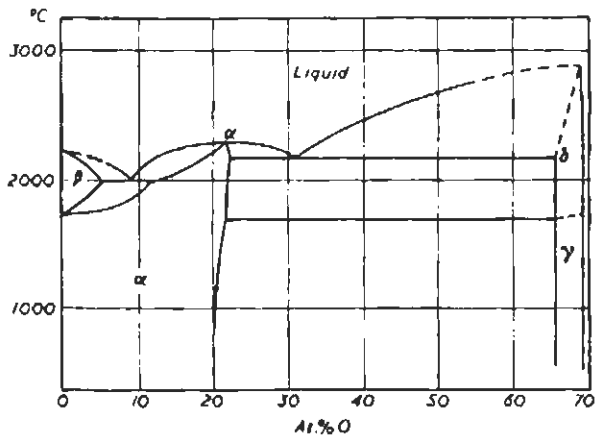
Hf–Nb


Wt. %Hf
°C
10 20 30 40 50 60 70 80 90
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
2468°
Liquid
2190°
2100°
β solid solution
1750°
α
0 20 40 60 80 100
At %Hf

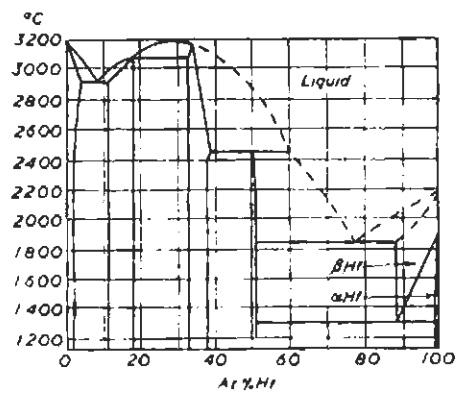
Hf–Ni



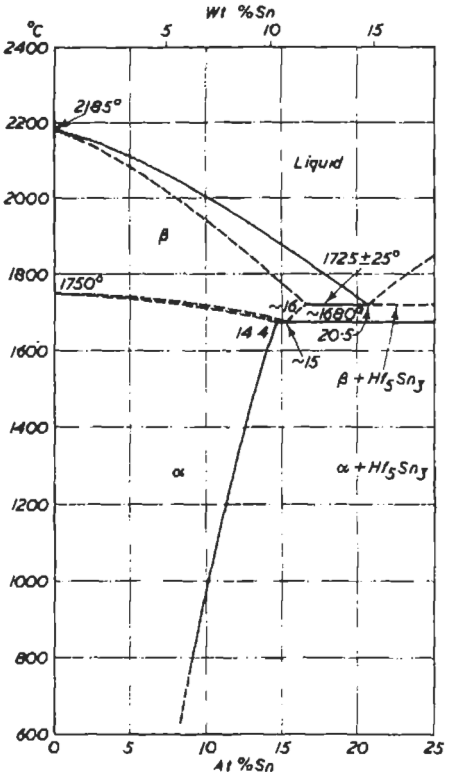
Hf–O



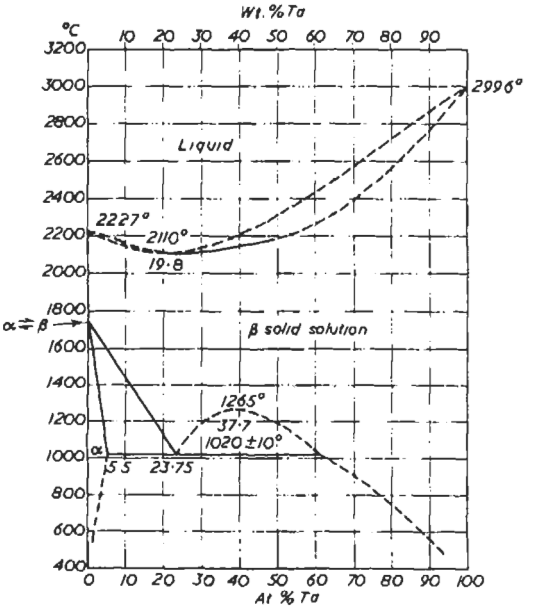
Hf–Re



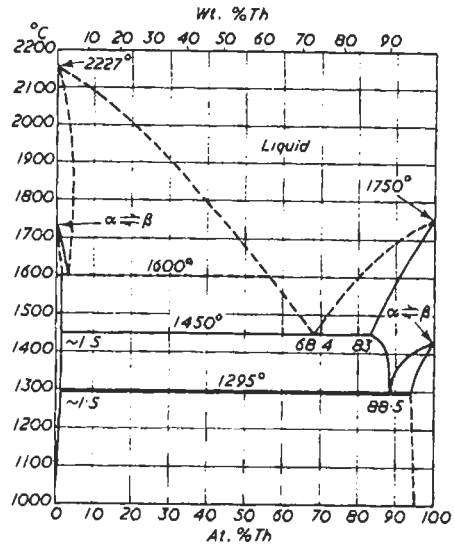
Hf–Sn


Wt %Sn
°C
5
10
15
2400
2200
2000
1800
1600
1400
1200
1000
800
600
2185°
Liquid
β
1725±25°
1750°
~16
~1680°
14·4
20·5
~15
β + Hf5Sn3
α
α + Hf5Sn3
0
5
10
15
20
25
At %Sn

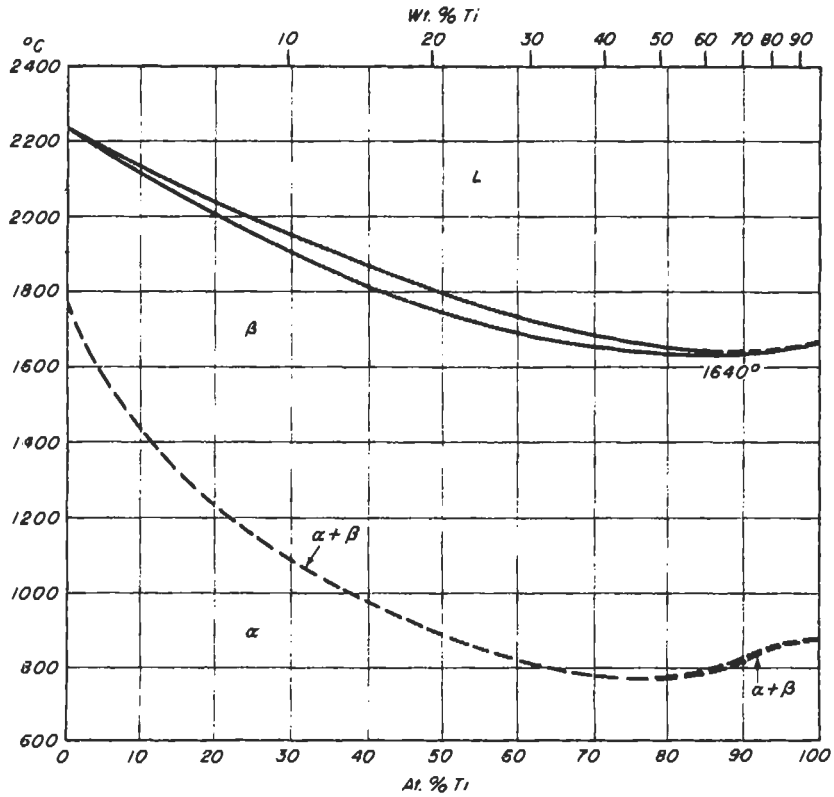
Hf–Ta


Wt. % Ta
°C
10
20
30
40
50
60
70
80
90
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
2996°
Liquid
2227°
2110°
19·8
α ⇌ β
β solid solution
1265°
37·7
1020±10°
α
5·5
23·75
0
10
20
30
40
50
60
70
80
90
100
At % Ta

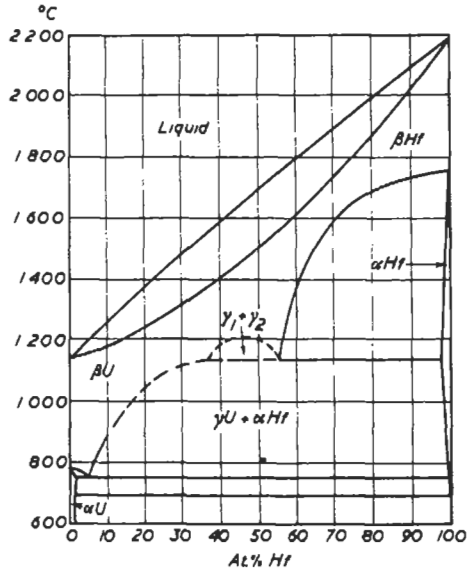
Hf–Th


Wt. %Th
°C
10 20 30 40 50 60 70 80 90
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
2227°
Liquid
1750°
α ⇌ β
1600°
1450°
~1·5
68·4
83
α ⇌ β
1295°
~1·5
88·5
0 10 20 30 40 50 60 70 80 90 100
At. %Th

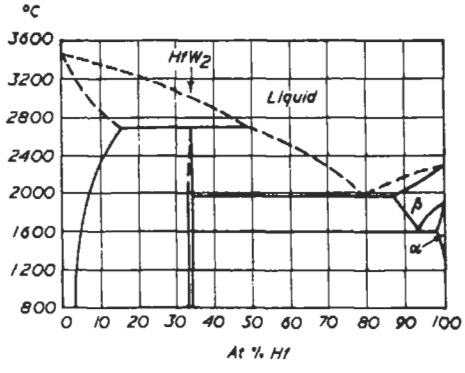
Hf–Ti


Wt. % Ti
°C
10 20 30 40 50 60 70 80 90
2400
2200
2000
1800
1600
1400
1200
1000
800
600
L
β
1640°
α + β
α
α + β
0 10 20 30 40 50 60 70 80 90 100
At. % Ti

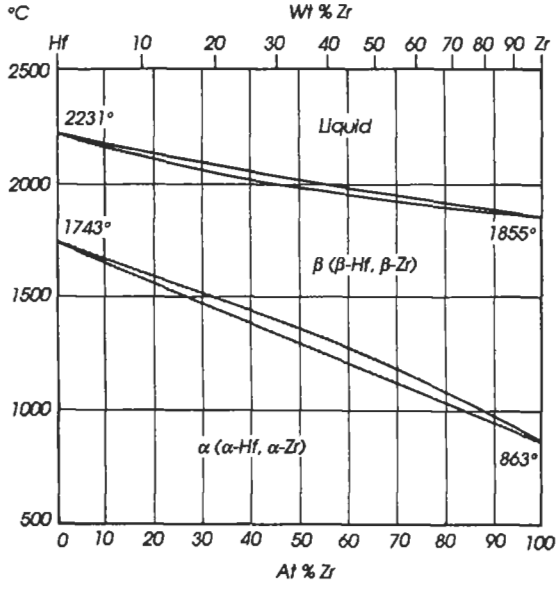
Hf–U


°C
2 200
2 000
1 800
1 600
1 400
1 200
1 000
800
600
Liquid
βHf
αHf
γ1 + γ2
βU
γU + αHf
αU
0 10 20 30 40 50 60 70 80 90 100
At% Hf

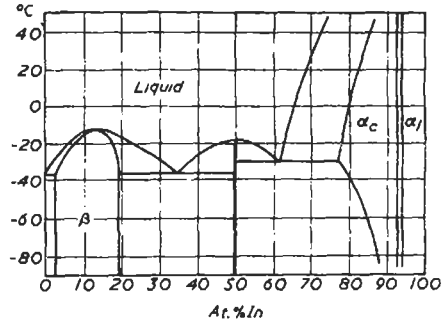
Hf–W


°C
3600
3200
2800
2400
2000
1600
1200
800
HfW2
Liquid
β
α
0 10 20 30 40 50 60 70 80 90 100
At % Hf

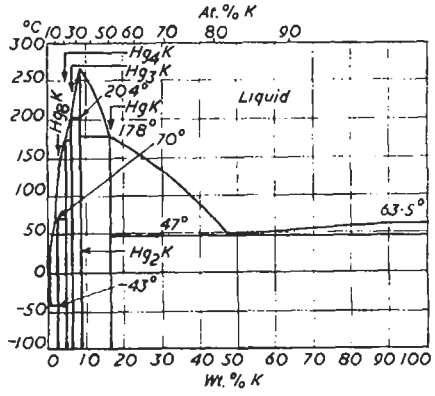
Hf–Zr


°C
Wt % Zr
Hf 10 20 30 40 50 60 70 80 90 Zr
2500
2000
1500
1000
500
2231°
Liquid
1855°
1743°
β (β-Hf, β-Zr)
α (α-Hf, α-Zr)
863°
0 10 20 30 40 50 60 70 80 90 100
At % Zr

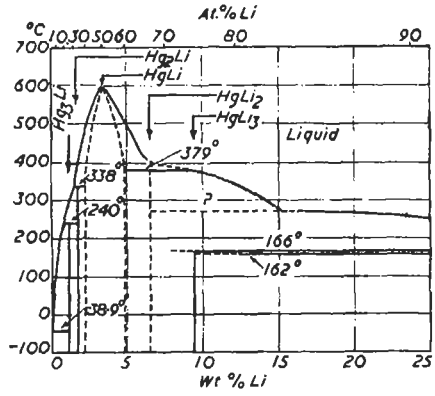
Hg–In



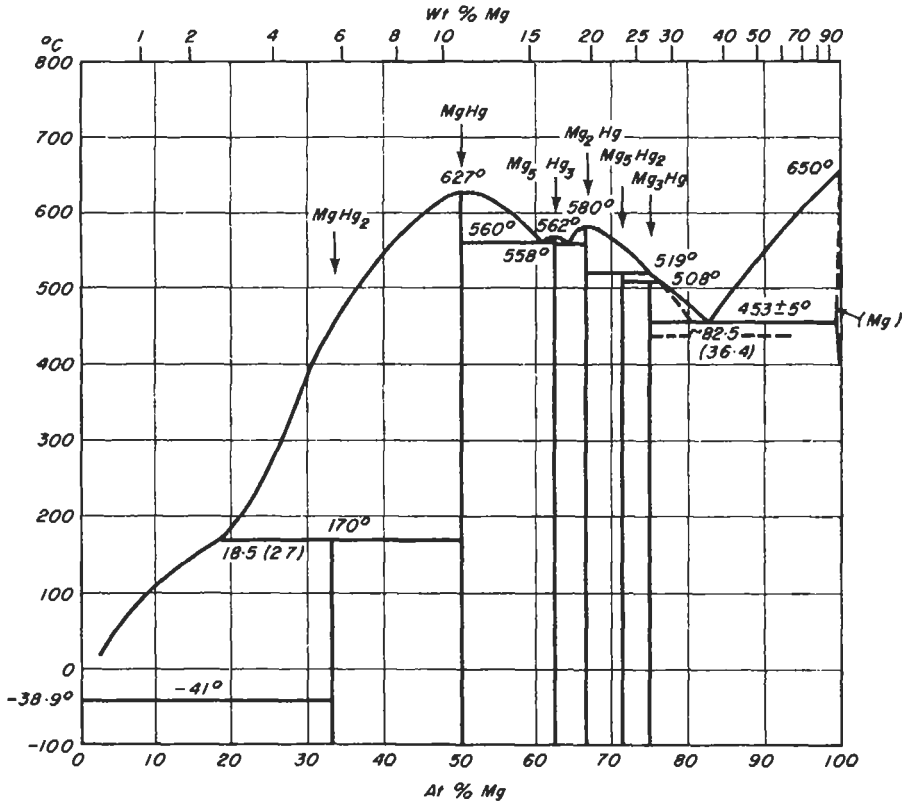
Hg–K



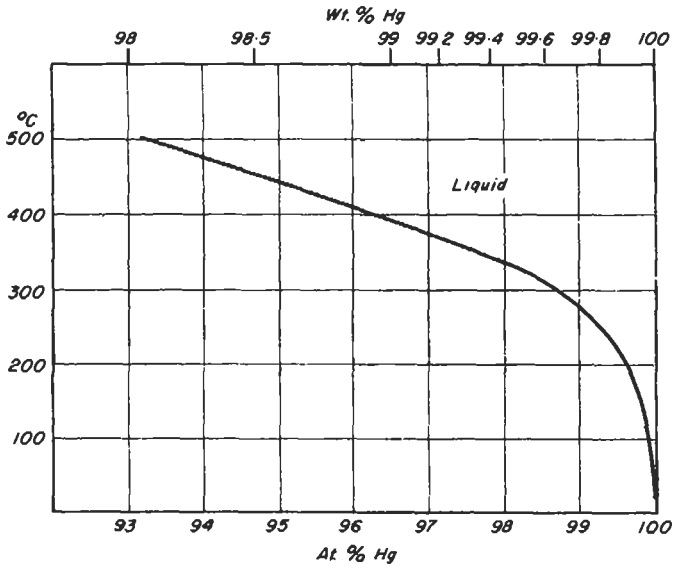
Hg–Li



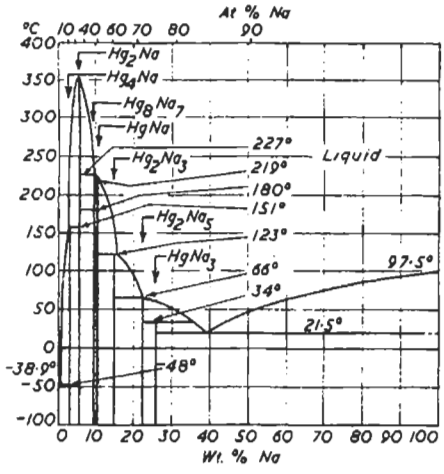
Hg–Mg


Wt % Mg
°C
1 2 4 6 8 10 15 20 25 30 40 50 70 90
800
700
600
500
400
300
200
100
0
-38·9°
-100
MgHg
627°
Mg2Hg
Mg5Hg2
Mg5Hg3
Mg3Hg
580°
650°
MgHg2
560°
562°
558°
519°
508°
453±5°
(Mg)
~82·5
(36·4)
170°
18·5 (27)
-41°
0 10 20 30 40 50 60 70 80 90 100
At % Mg

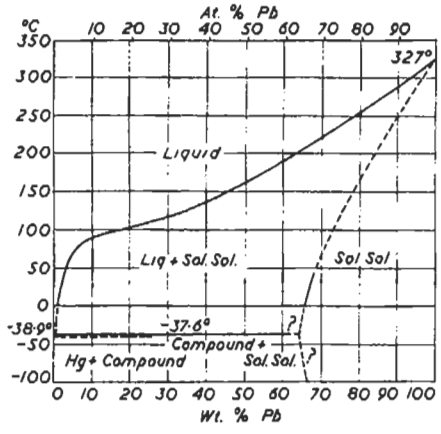
Hg–Mn


Wt. % Hg
98 98·5 99 99·2 99·4 99·6 99·8 100
°C
500
400
300
200
100
Liquid
93 94 95 96 97 98 99 100
At % Hg

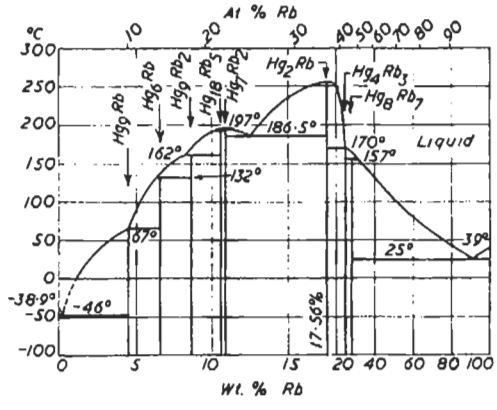
Hg–Na



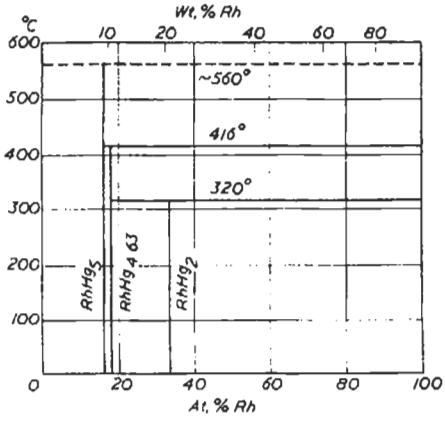
Hg–Pb



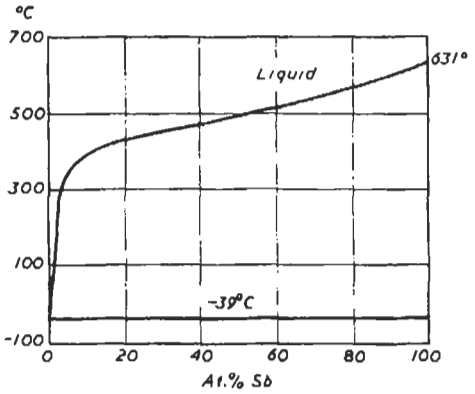
Hg–Rb



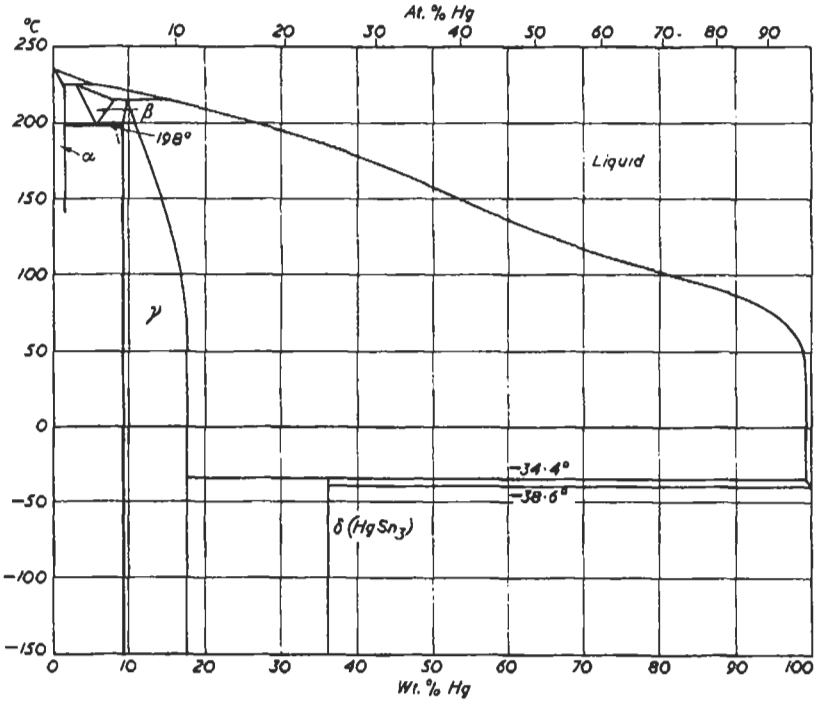
Hg–Rh



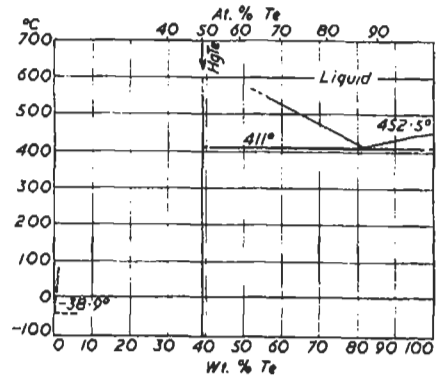
Hg–Sb



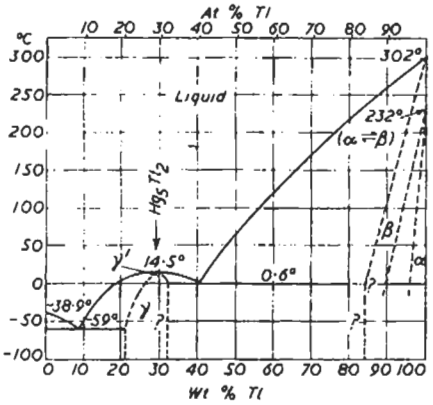
Hg–Sn



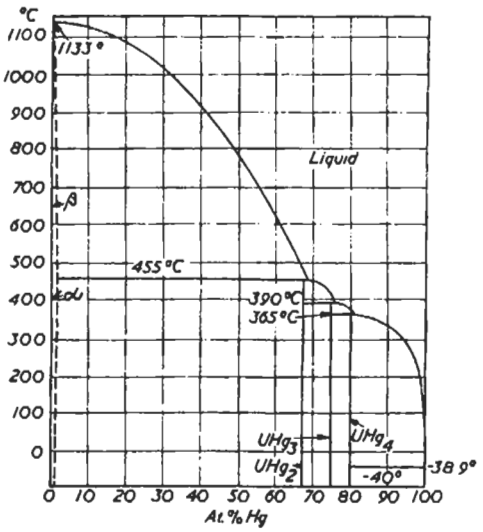
Hg–Te



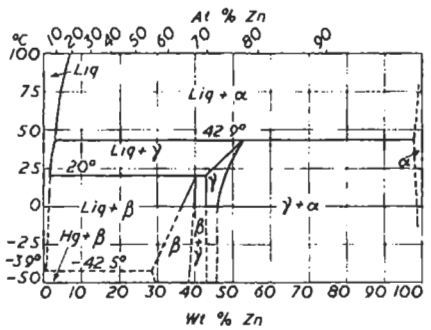
Hg–Tl



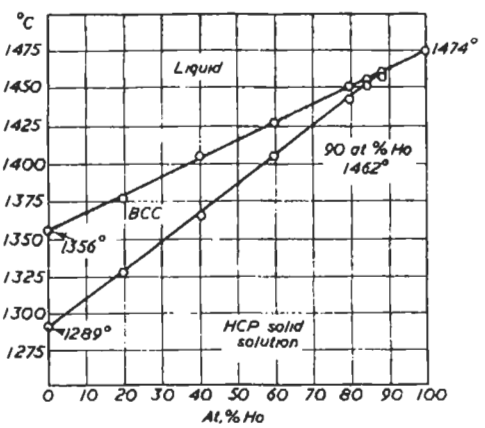
Hg–U



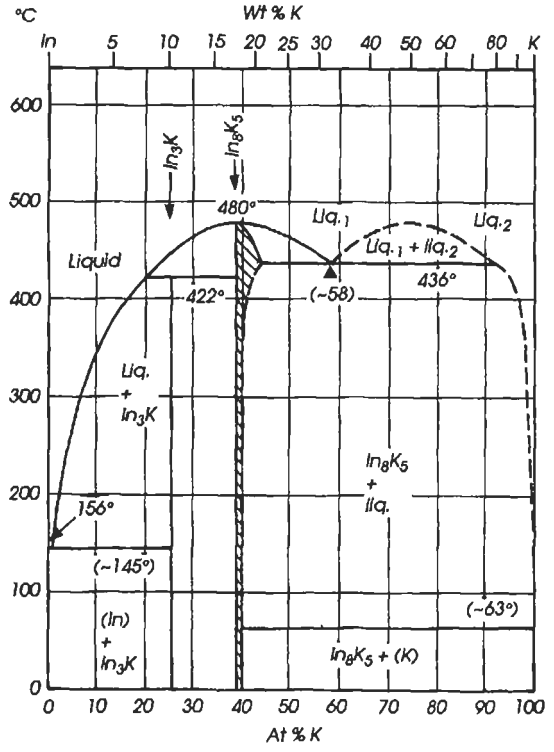
Hg–Zn



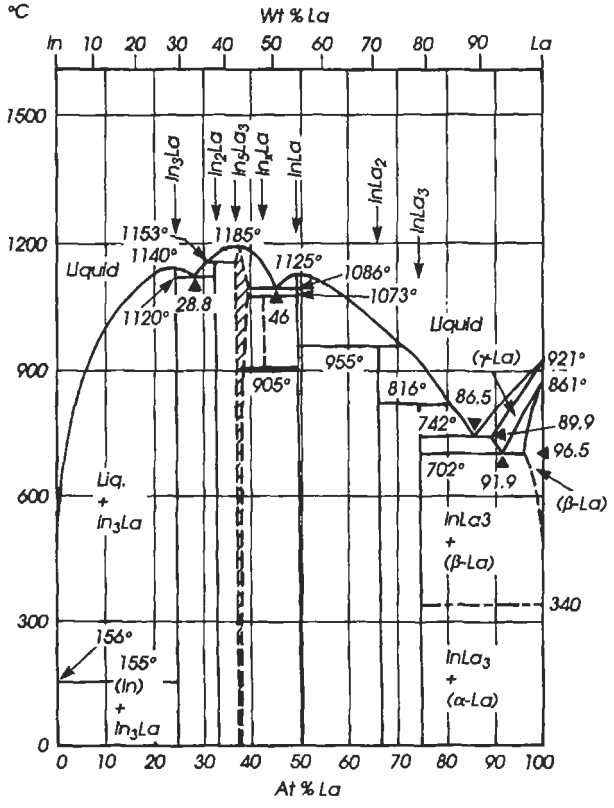
Ho–Tb



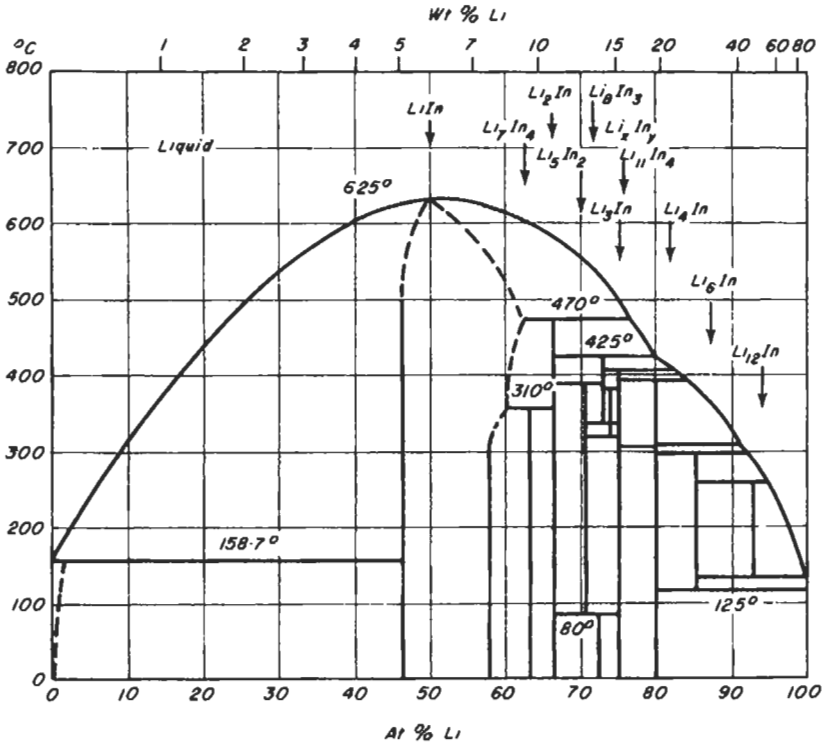
In–K


°C
Wt % K
In 5 10 15 20 25 30 40 50 60 80 K
600
500
400
300
200
100
0
In_3K
In_8K_5
480°
Liq.1
Liq.2
Liq.1 + liq.2
Liquid
422°
(~58)
436°
Liq. + In_3K
In_8K_5 + liq.
156°
(~145°)
(~63°)
(In) + In_3K
In_8K_5 + (K)
0 10 20 30 40 50 60 70 80 90 100
At % K

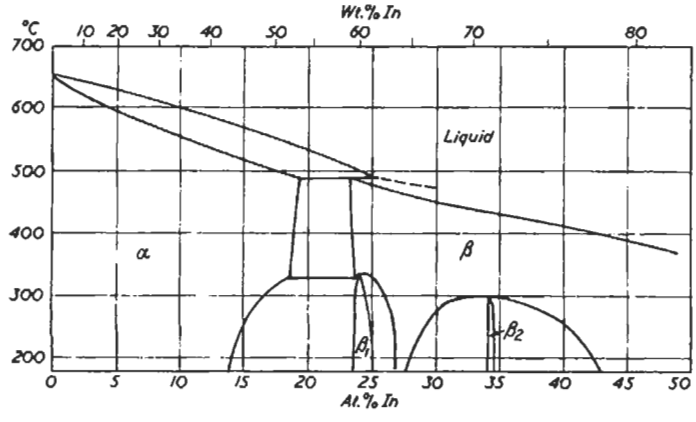
In–La


°C
Wt % La
In 10 20 30 40 50 60 70 80 90 La
1500
1200
900
600
300
0
In_3La
In_2La
In_5La_3
In_1La
InLa
$InLa_2$
$InLa_3$
1153°
1185°
1140°
1125°
1086°
1073°
Liquid
1120°
28.8
46
955°
905°
816°
86.5
742°
89.9
96.5
702°
91.9
(γ-La)
921°
861°
(β-La)
340
Liq. + In_3La
InLa3 + (β-La)
156°
155°
(In) + In_3La
$InLa_3$ + (α-La)
0 10 20 30 40 50 60 70 80 90 100
At % La

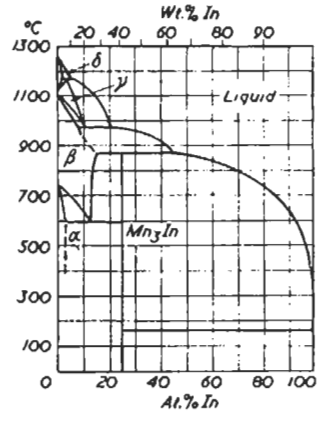
In–Li



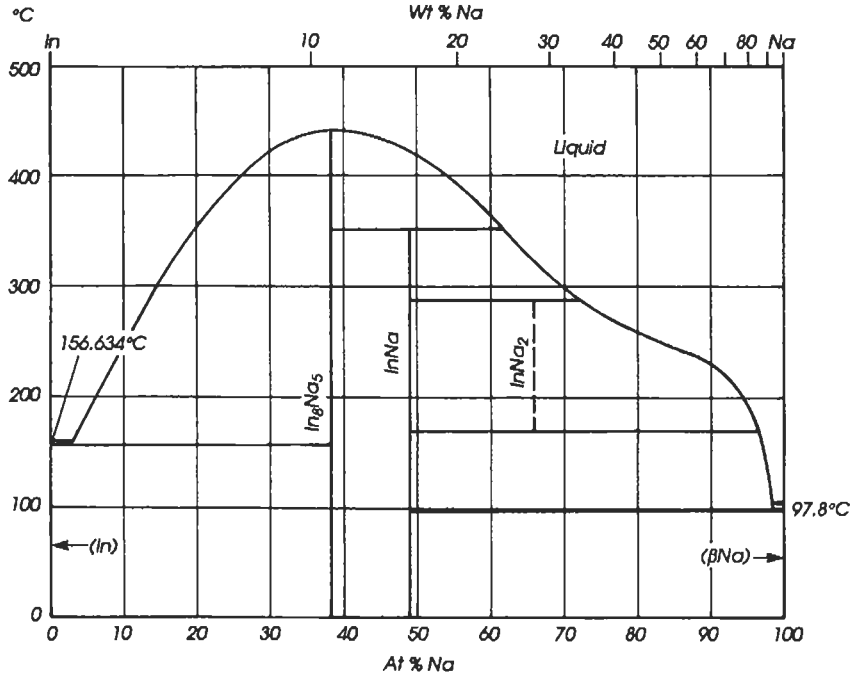
In–Mg



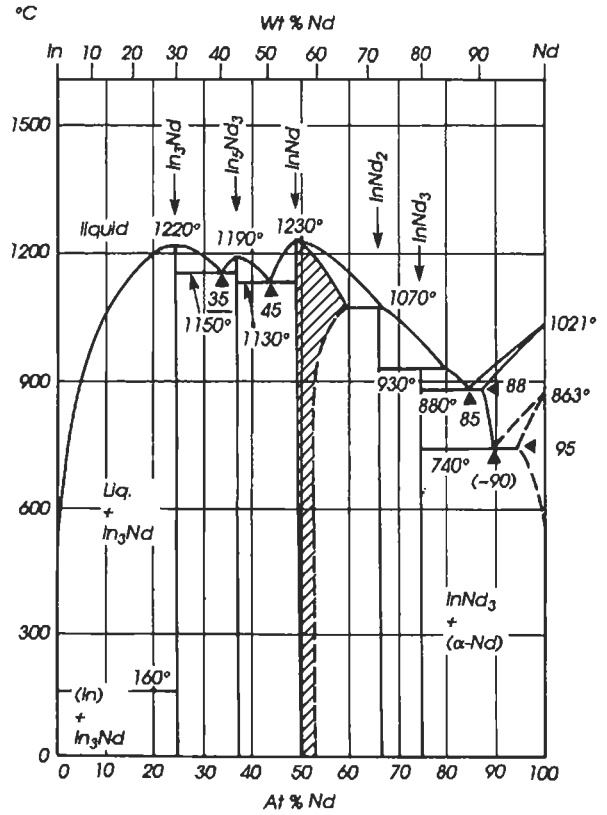
In–Mn



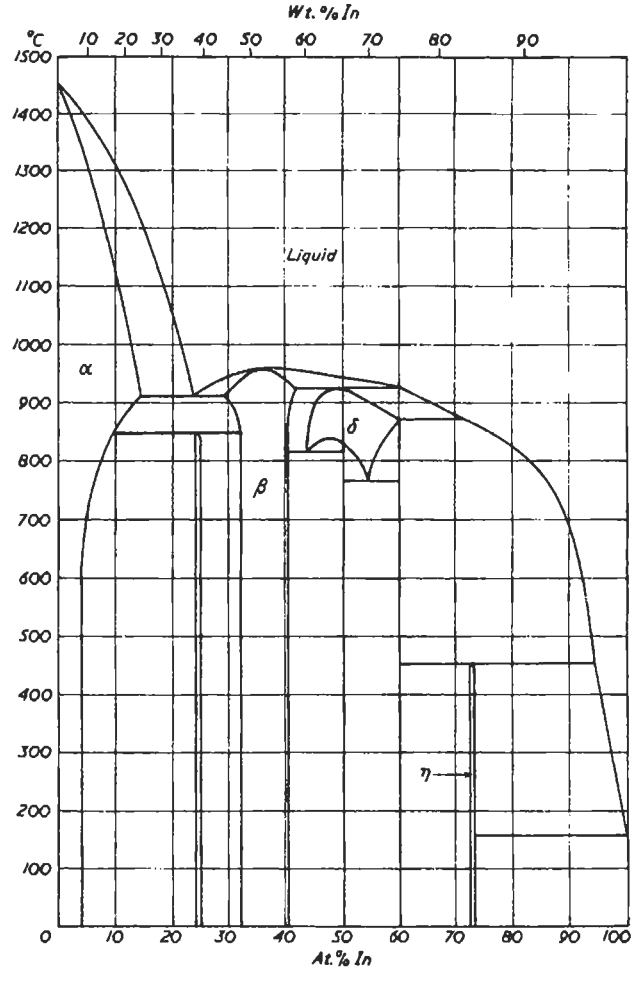
In–Na


°C
Wt % Na
In
10
20
30
40
50
60
80
Na
500
400
300
200
100
0
Liquid
156.634°C
In_8Na_5
InNa
$InNa_2$
97.8°C
(In)
(βNa)
0
10
20
30
40
50
60
70
80
90
100
At % Na

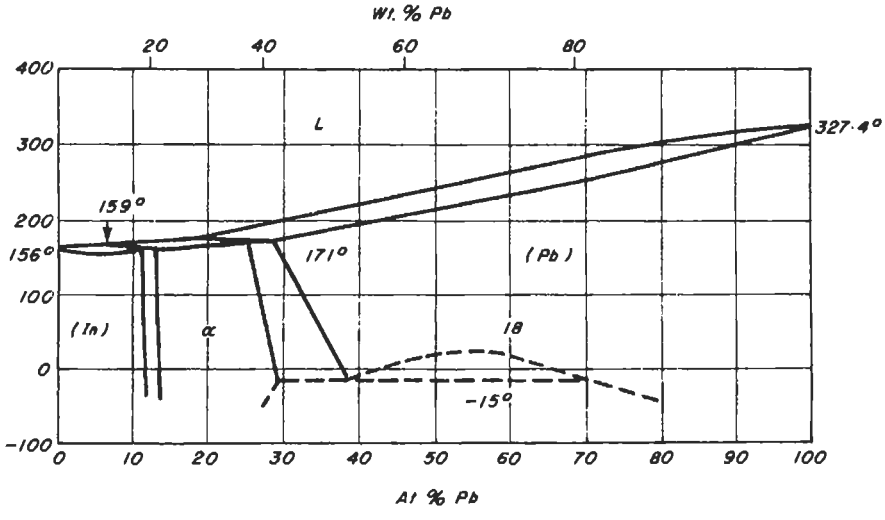
In–Nd


°C
Wt % Nd
In
10
20
30
40
50
60
70
80
90
Nd
1500
1200
900
600
300
0
In_3Nd
In_5Nd_3
InNd
$InNd_2$
$InNd_3$
liquid
1220°
1190°
1230°
1070°
1021°
35
1150°
45
1130°
930°
88
880°
85
863°
740°
(~90)
95
Liq.
+
In_3Nd
160°
(In)
+
In_3Nd
$InNd_3$
+
(α-Nd)
0
10
20
30
40
50
60
70
80
90
100
At % Nd

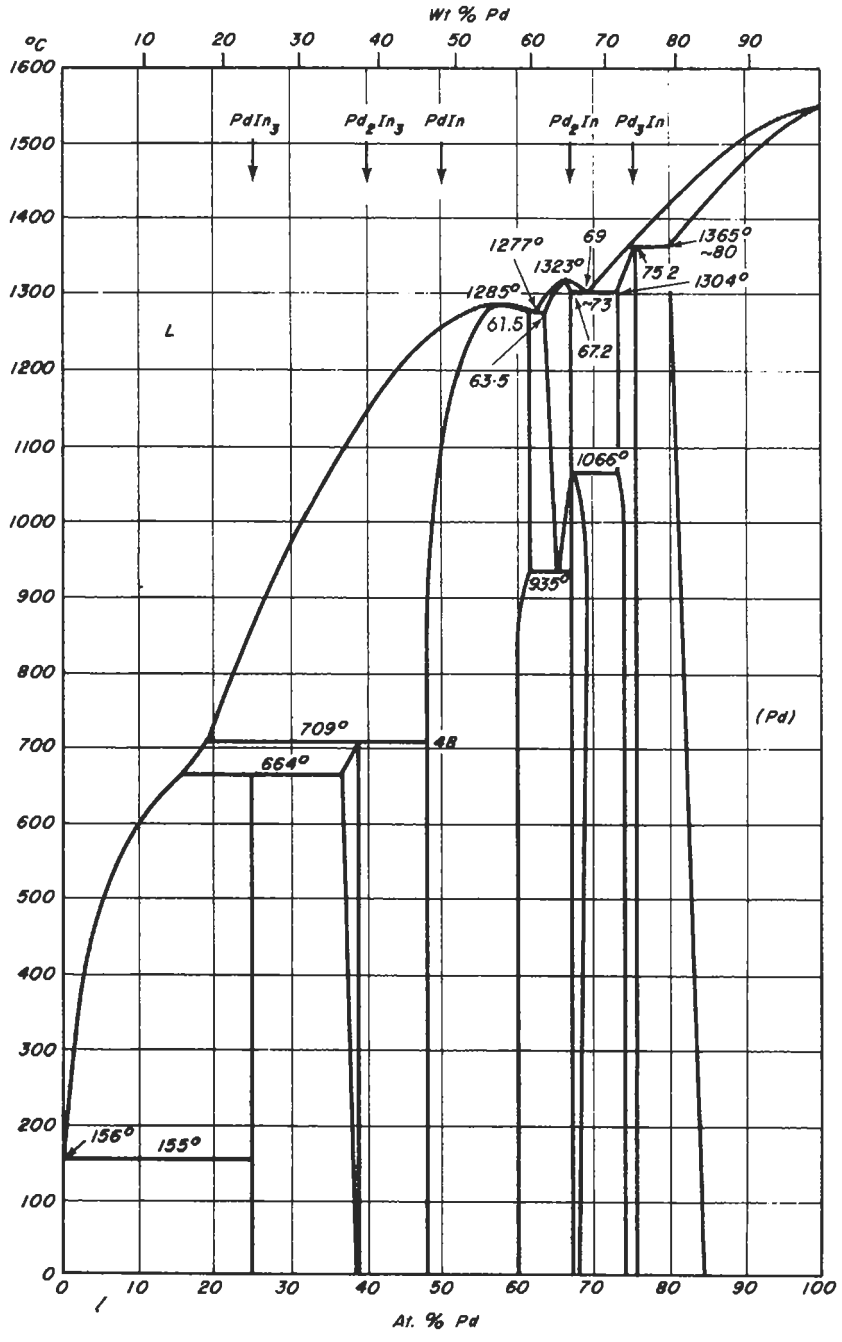
In–Ni


Wt. % In
°C
10 20 30 40 50 60 70 80 90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Liquid
α
β
δ
η
10 20 30 40 50 60 70 80 90 100
At. % In

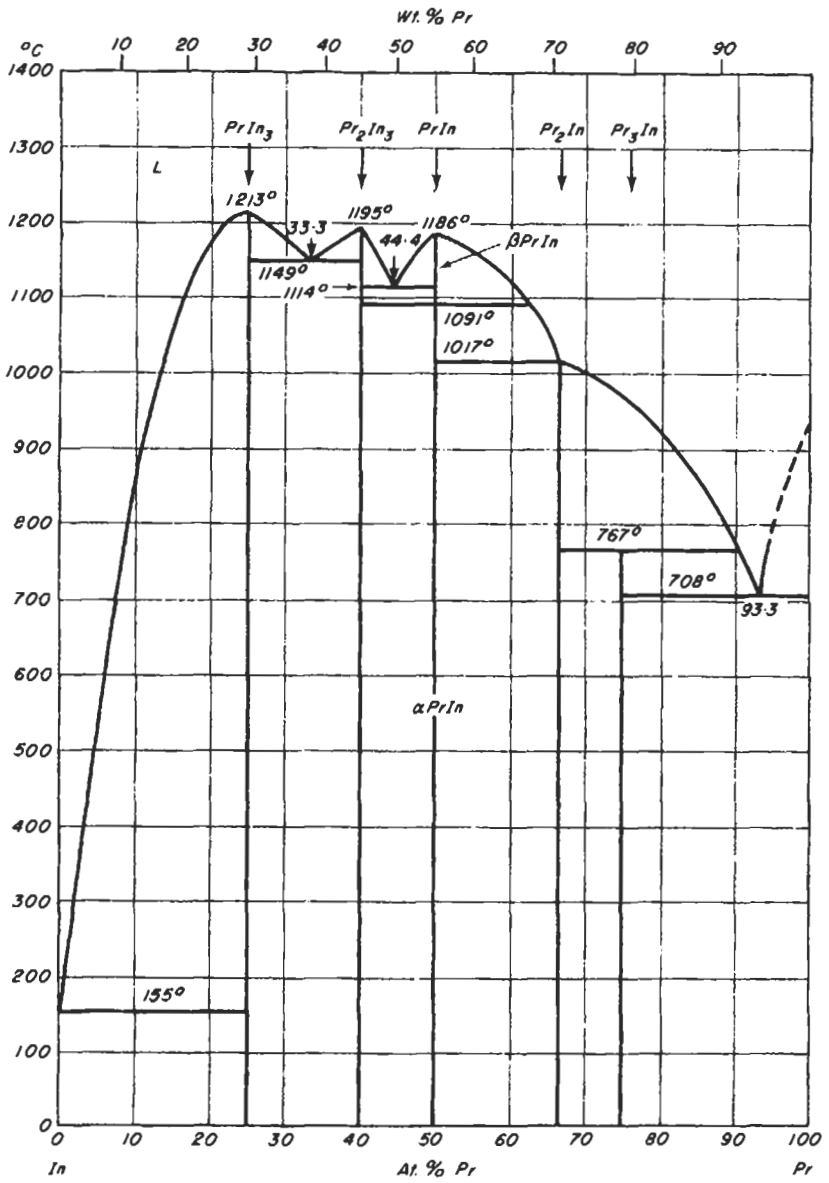
In–Pb


Wt. % Pb
20 40 60 80
400
300
200
156°
100
0
−100
L
327·4°
159°
171°
(Pb)
(In)
α
18
−15°
0 10 20 30 40 50 60 70 80 90 100
At % Pb

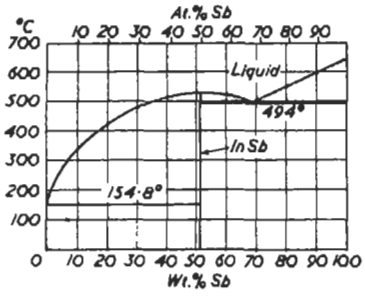
In–Pd


Wt % Pd
°C
10
20
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
PdIn3
Pd2In3
PdIn
Pd2In
Pd3In
1277°
69
1323°
1365°
~80
75·2
1304°
1285°
~73
61.5
67.2
63·5
1066°
935°
L
709°
48
664°
(Pd)
156°
155°
At. % Pd

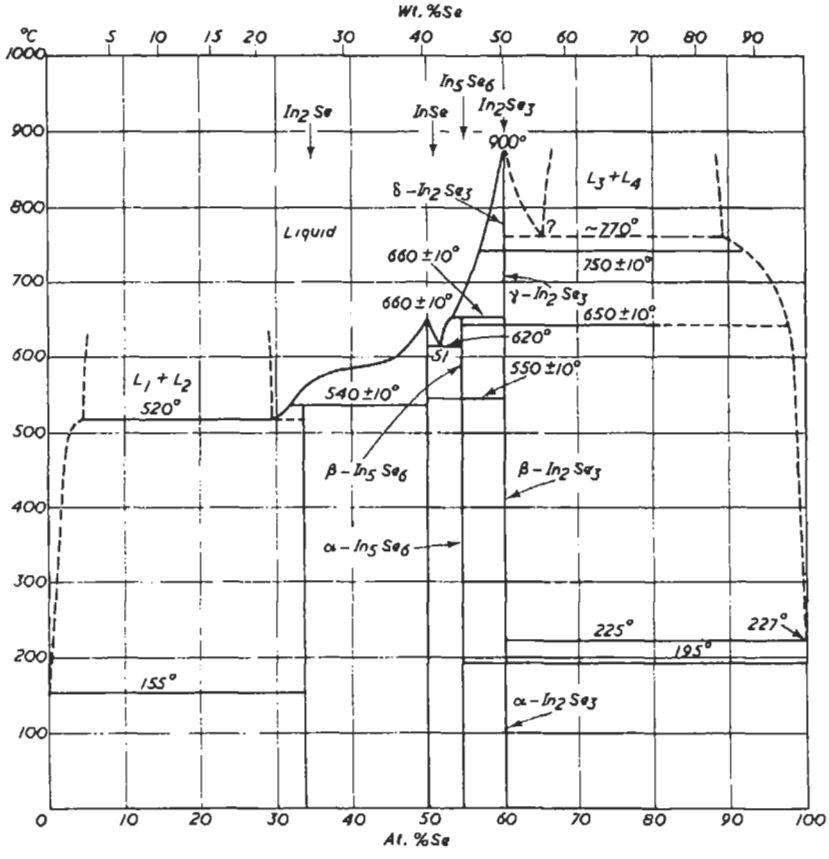
In–Pr


Wt. % Pr
°C
10
20
30
40
50
60
70
80
90
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
$PrIn_3$
Pr_2In_3
PrIn
Pr_2In
Pr_3In
L
1213°
33·3
1195°
44·4
1186°
βPrIn
1149°
1114°
1091°
1017°
767°
708°
93·3
αPrIn
155°
0
10
20
30
40
50
60
70
80
90
100
In
At. % Pr
Pr

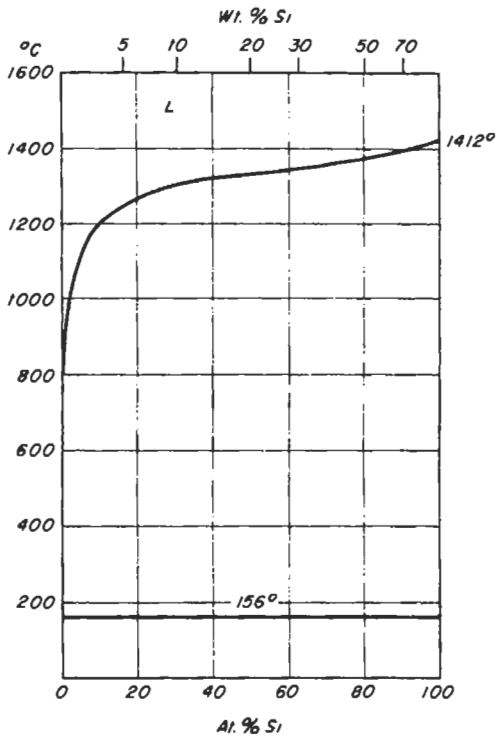
In–Sb


°C
At.% Sb
10 20 30 40 50 60 70 80 90
700
600
500
400
300
200
100
0
Liquid
494°
InSb
154·8°
Wt.% Sb

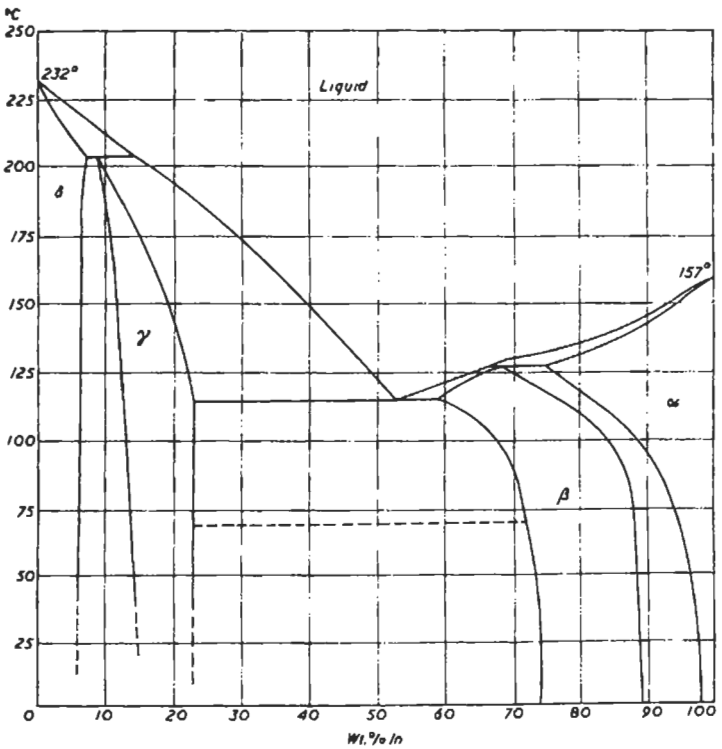
In–Se


Wt.%Se
°C
5 10 15 20 30 40 50 60 70 80 90
1000
900
800
700
600
500
400
300
200
100
0
In2Se
InSe
In5Se6
In2Se3
900°
L3+L4
δ-In2Se3
Liquid
660±10°
?
~270°
750±10°
γ-In2Se3
660±10°
650±10°
620°
51
550±10°
L1+L2
520°
540±10°
β-In5Se6
β-In2Se3
α-In5Se6
225°
227°
195°
155°
α-In2Se3
10 20 30 40 50 60 70 80 90 100
At.%Se

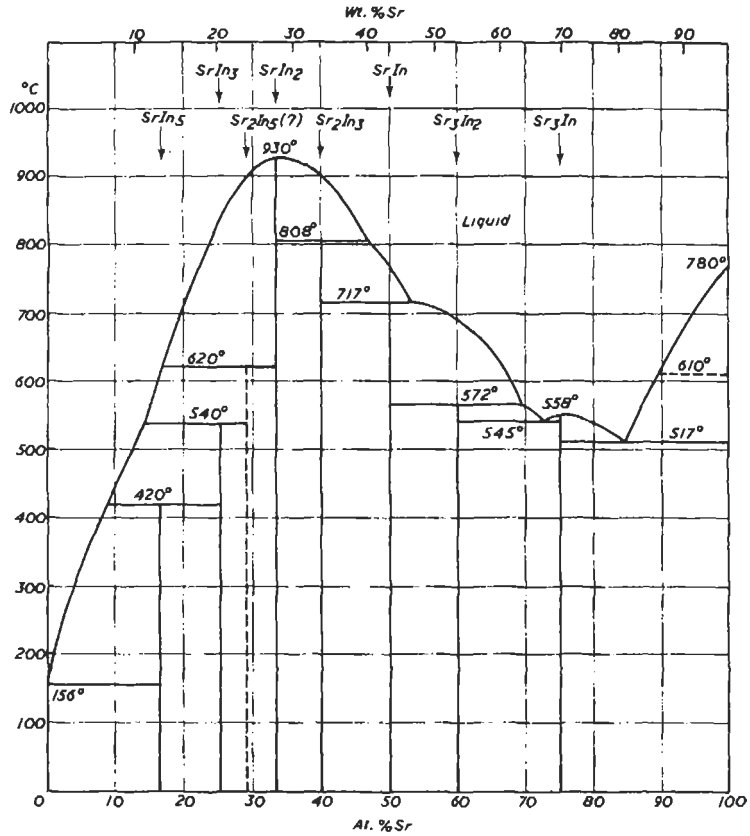
In–Si


Wt. % Si
°C
5
10
20
30
50
70
1600
1400
1200
1000
800
600
400
200
L
1412°
156°
0
20
40
60
80
100
At. % Si

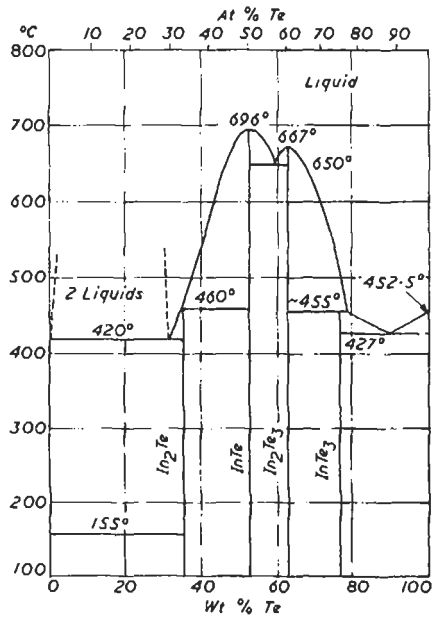
In–Sn


°C
250
225
200
175
150
125
100
75
50
25
0
232°
Liquid
δ
γ
157°
α
β
10
20
30
40
50
60
70
80
90
100
Wt.% In

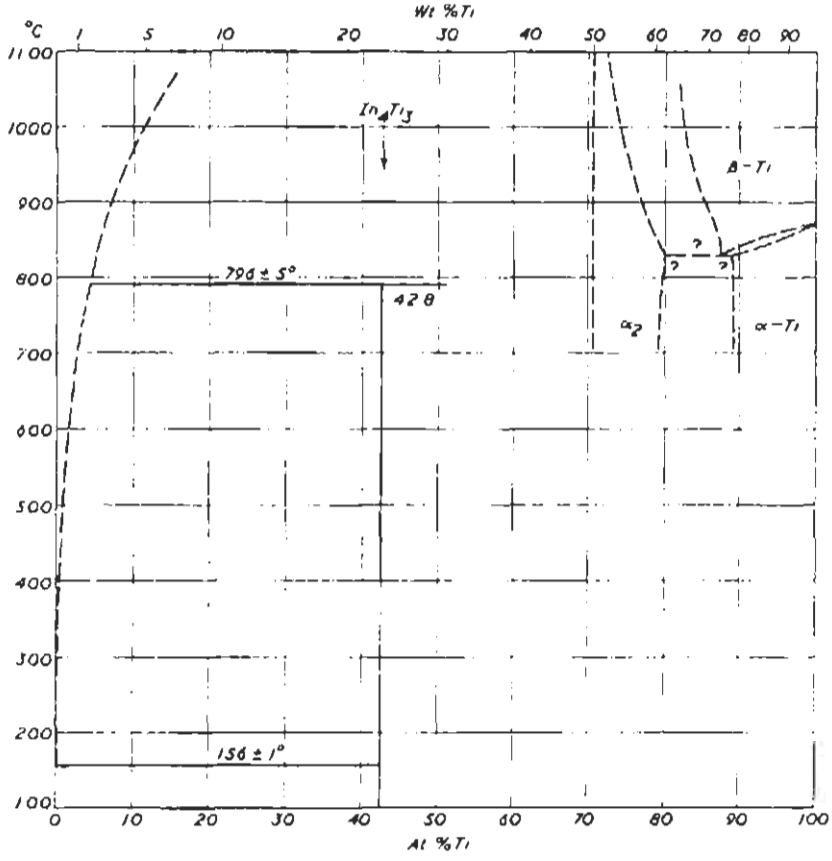
In–Sr


Wt. % Sr
10 20 30 40 50 60 70 80 90
°C
1000 900 800 700 600 500 400 300 200 100
SrIn3 SrIn2 SrIn
Sr2In5 Sr2In5(?) Sr2In3 Sr5In2 Sr3In
930°
808°
717°
620°
540°
420°
156°
Liquid
780°
610°
572°
558°
545°
517°
0 10 20 30 40 50 60 70 80 90 100
At. % Sr

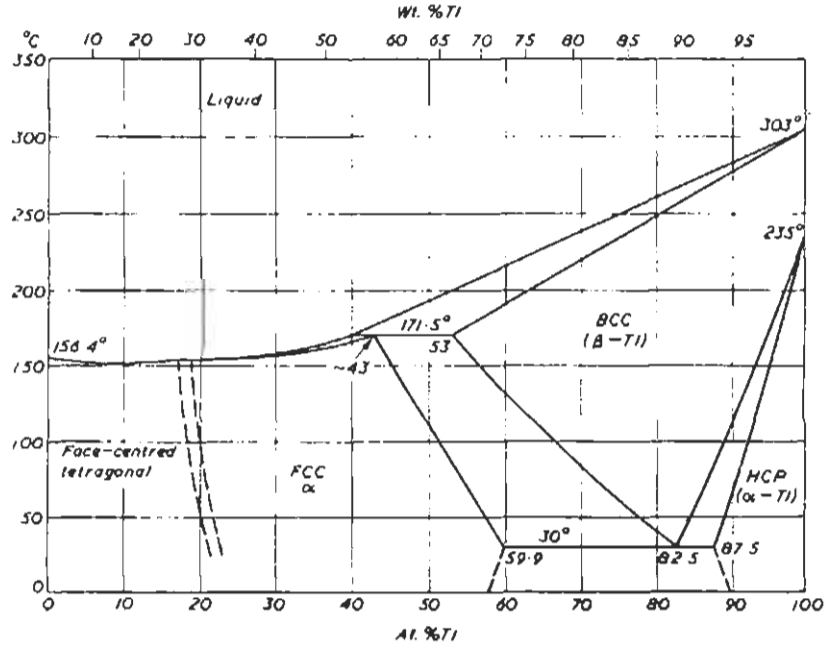
In–Te


At % Te
°C
10 20 30 40 50 60 70 80 90
800 700 600 500 400 300 200 100
Liquid
696°
667°
650°
2 Liquids
460°
420°
~455°
452·5°
427°
In2Te
InTe
In2Te3
InTe3
155°
0 20 40 60 80 100
Wt % Te

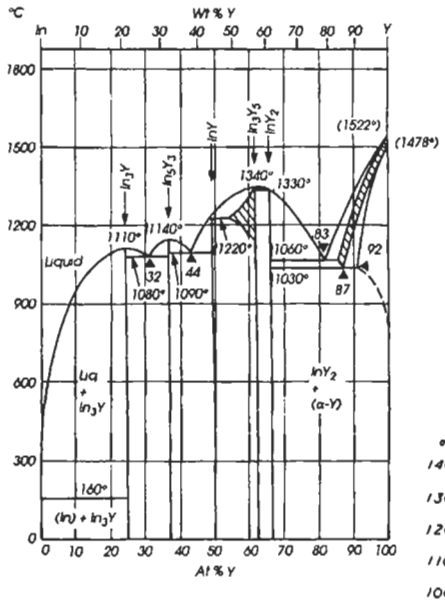
In–Ti


Wt %Ti
°C
1100
1000
900
800
700
600
500
400
300
200
100
1 5 10 20 30 40 50 60 70 80 90
0 10 20 30 40 50 60 70 80 90 100
At %Ti
In_4Ti_3
β-Ti
798 ± 5°
42 8
α_2
α-Ti
156 ± 1°
? ? ?

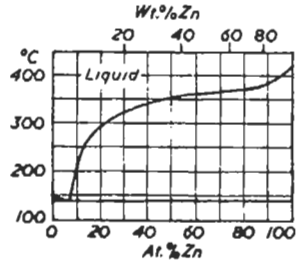
In–Tl


Wt. %Tl
°C
350
300
250
200
150
100
50
0
10 20 30 40 50 60 65 70 75 80 85 90 95
0 10 20 30 40 50 60 70 80 90 100
At %Tl
Liquid
303°
235°
171·5°
53
156 4°
~43
BCC
(β-Tl)
Face-centred
tetragonal
FCC
α
HCP
(α-Tl)
30°
59·9
82 5
87 5

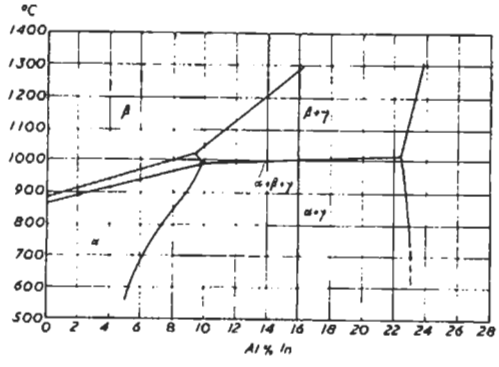
In–Y



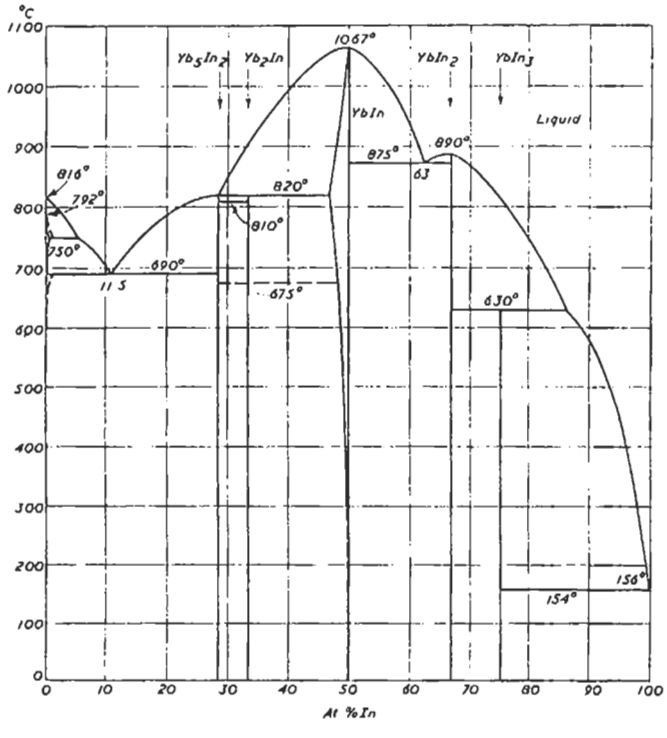
In–Zn



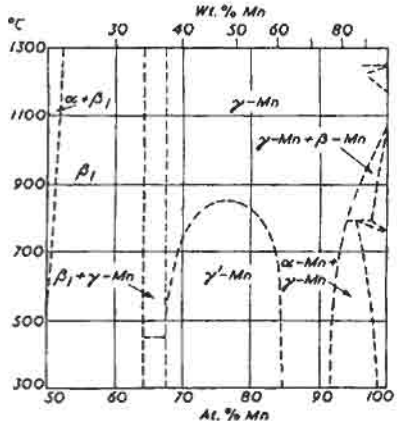
In–Zr



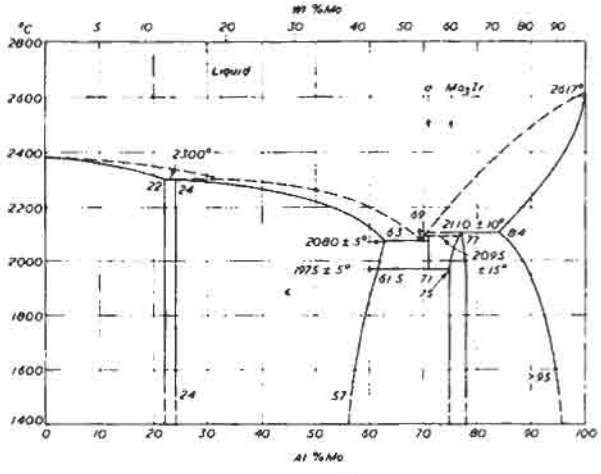
In–Yb



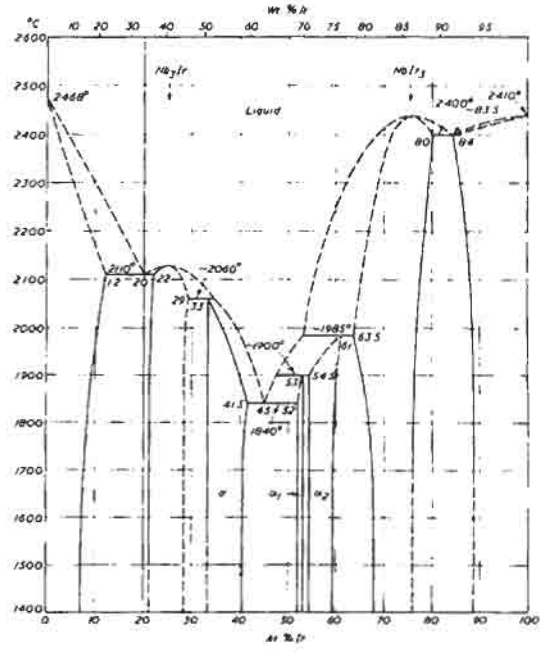
Ir–Mn



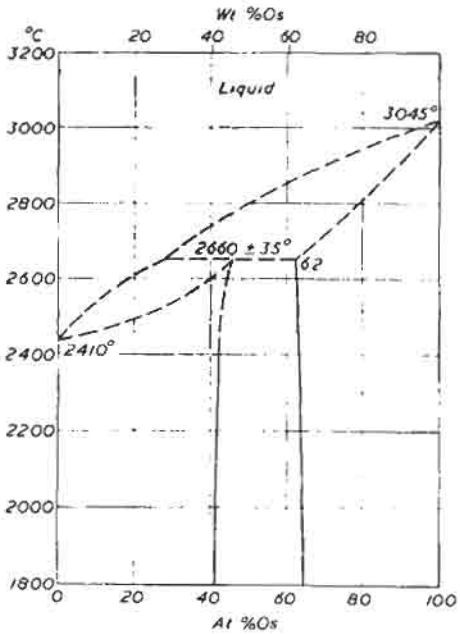
Ir–Mo



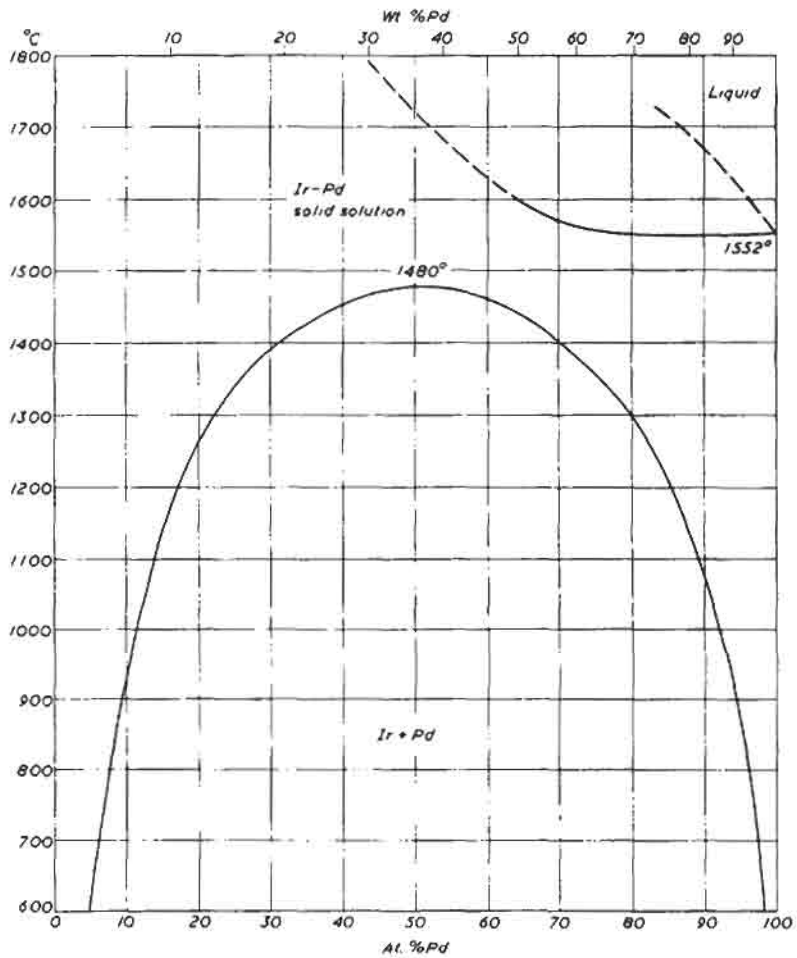
Ir–Nb



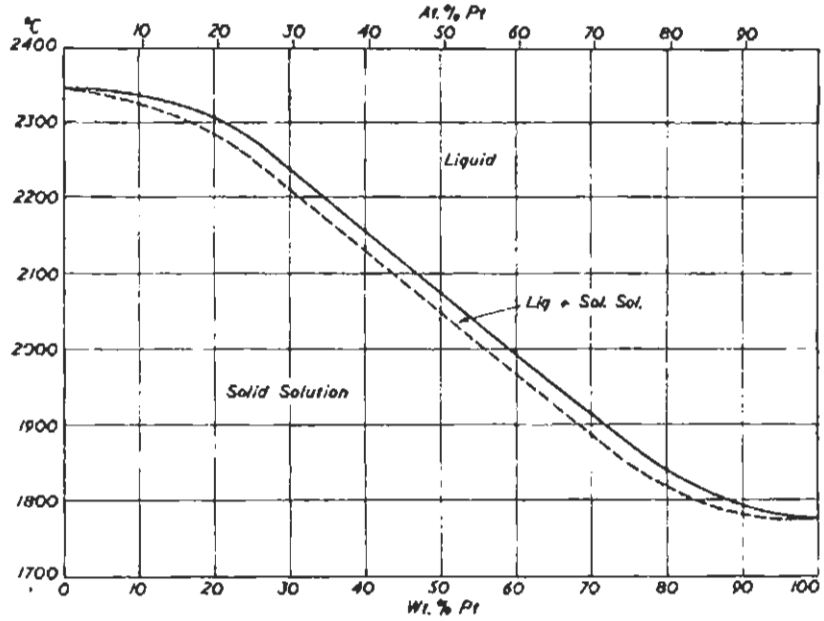
Ir–Os


Wt %Os
°C
20
40
60
80
3200
3000
2800
2600
2400
2200
2000
1800
Liquid
3045°
2660 ± 35°
62
2410°
0
20
40
60
80
100
At %Os

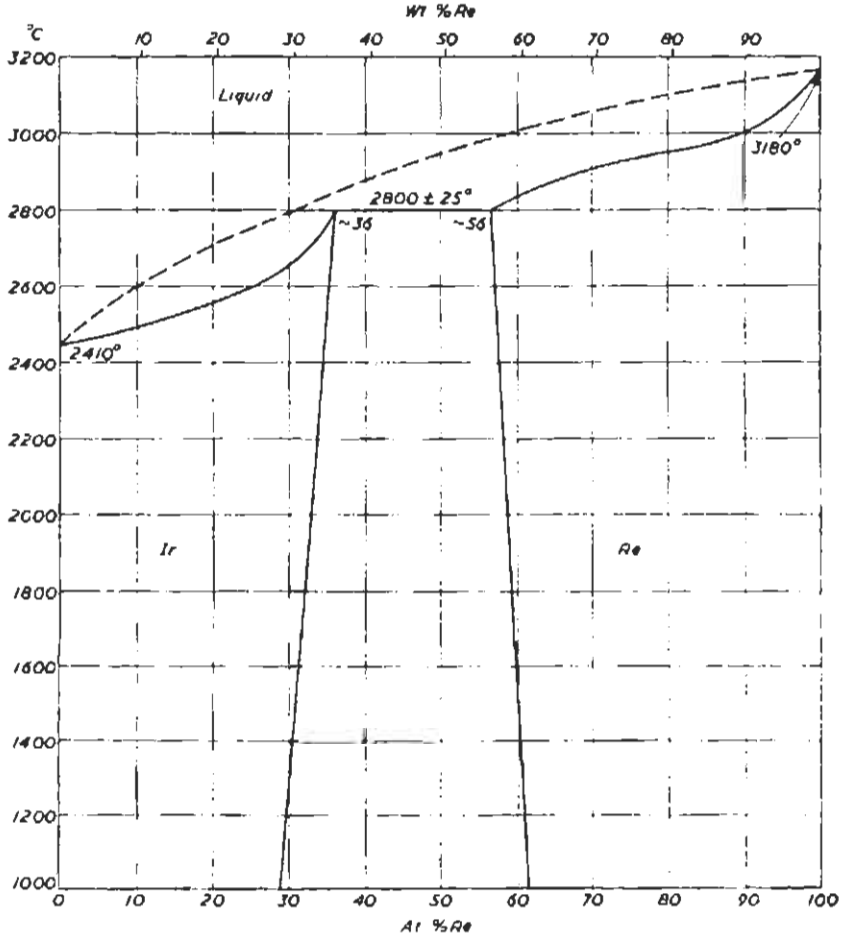
Ir–Pd


Wt %Pd
°C
10
20
30
40
50
60
70
80
90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
Liquid
Ir–Pd
solid solution
1552°
1480°
Ir + Pd
0
10
20
30
40
50
60
70
80
90
100
At. %Pd

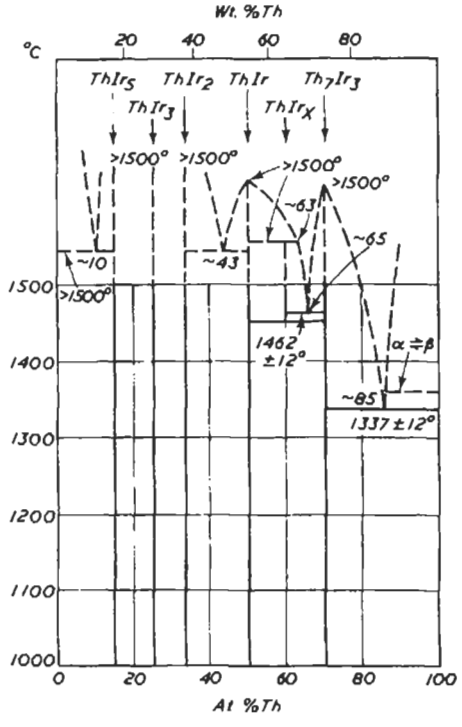
Ir–Pt


°C
At. % Pt
10 20 30 40 50 60 70 80 90
2400
2300
2200
2100
2000
1900
1800
1700
Liquid
Liq + Sol. Sol.
Solid Solution
0 10 20 30 40 50 60 70 80 90 100
Wt. % Pt

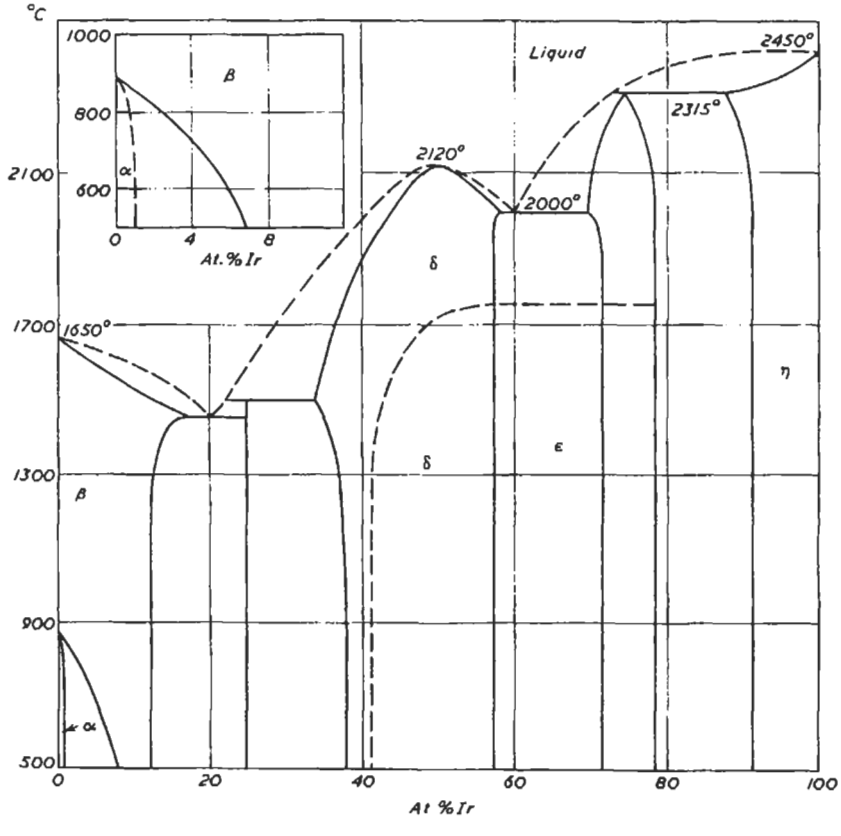
Ir–Re


Wt % Re
°C
10 20 30 40 50 60 70 80 90
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
Liquid
3180°
2800 ± 25°
~36
~56
2410°
Ir
Re
0 10 20 30 40 50 60 70 80 90 100
At % Re

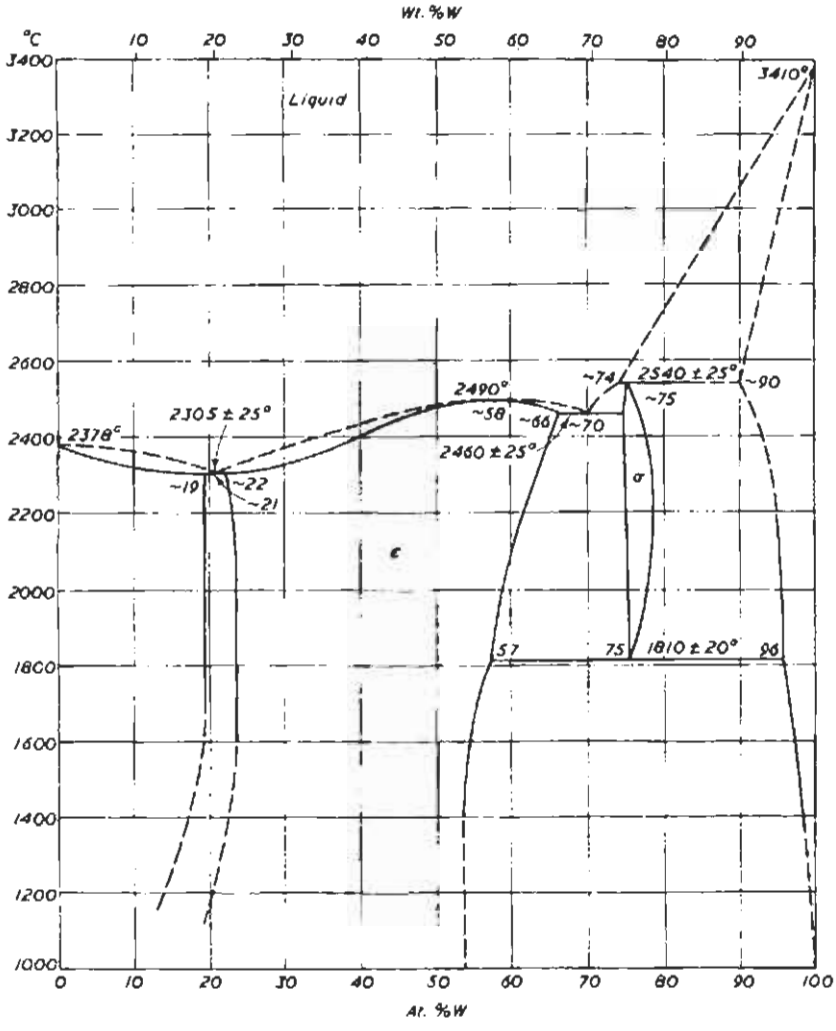
Ir–Th


Wt. %Th
°C
20
40
60
80
ThIr5
ThIr2
ThIr
Th7Ir3
ThIr3
ThIrX
>1500°
>1500°
>1500°
>1500°
~63
~65
~10
~43
>1500°
1462 ±12°
α ⇌ β
~85
1337 ±12°
1500
1400
1300
1200
1100
1000
0
20
40
60
80
100
At %Th

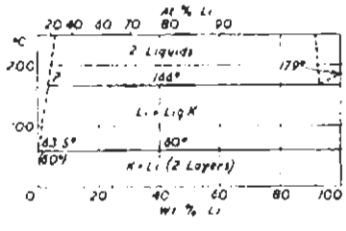
Ir–Ti


°C
1000
800
600
β
α
0
4
8
At.% Ir
Liquid
2450°
2315°
2120°
2000°
1650°
δ
η
ε
δ
β
α
2100
1700
1300
900
500
0
20
40
60
80
100
At %Ir

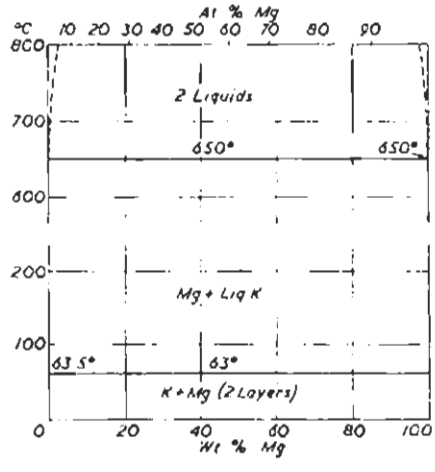
Ir–W


Wt. %W
°C
Liquid
3410°
2378°
2305 ± 25°
2490°
2460 ± 25°
2540 ± 25°
~74
~75
~90
~58
~66
~70
~19
~22
~21
σ
57
75
1810 ± 20°
96
At. %W

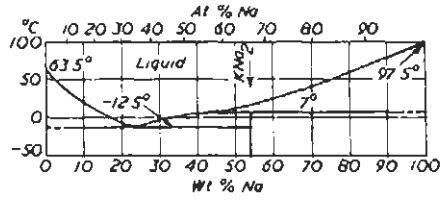
K–Li


At. % Li
°C
2 Liquids
179°
168°
L + Liq K
63.5°
60°
K + Li (2 Layers)
Wt. % Li

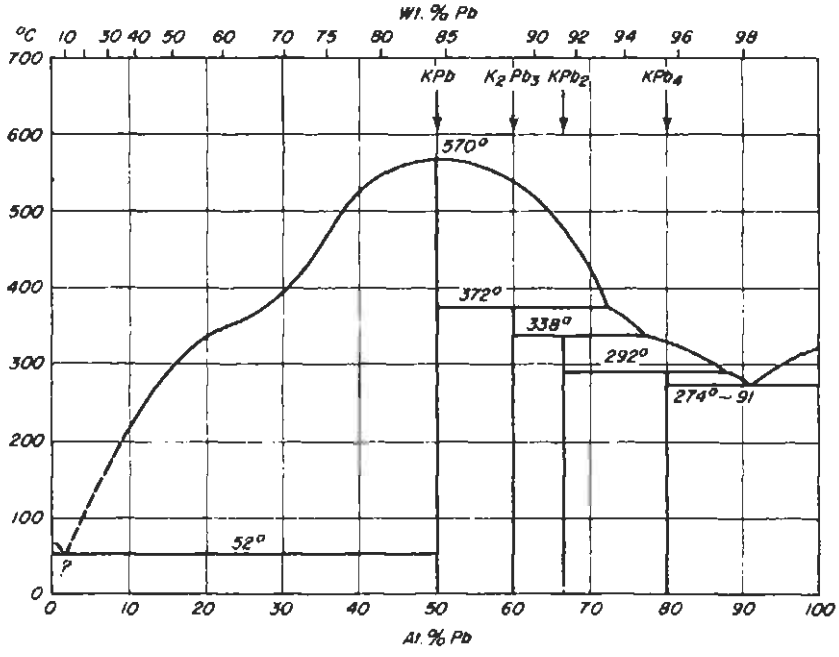
K–Mg


At. % Mg
°C
2 Liquids
650°
650°
Mg + Liq K
63.5°
63°
K + Mg (2 Layers)
Wt. % Mg

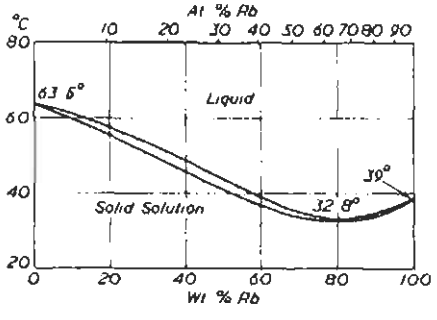
K–Na



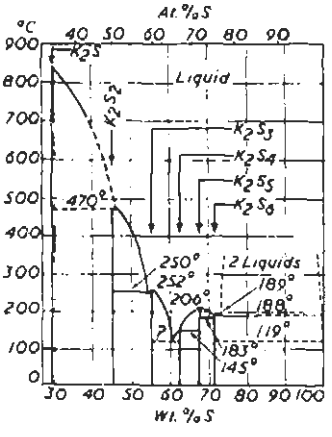
K–Pb



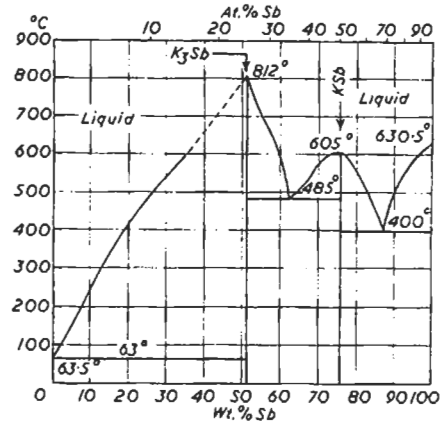
K–Rb



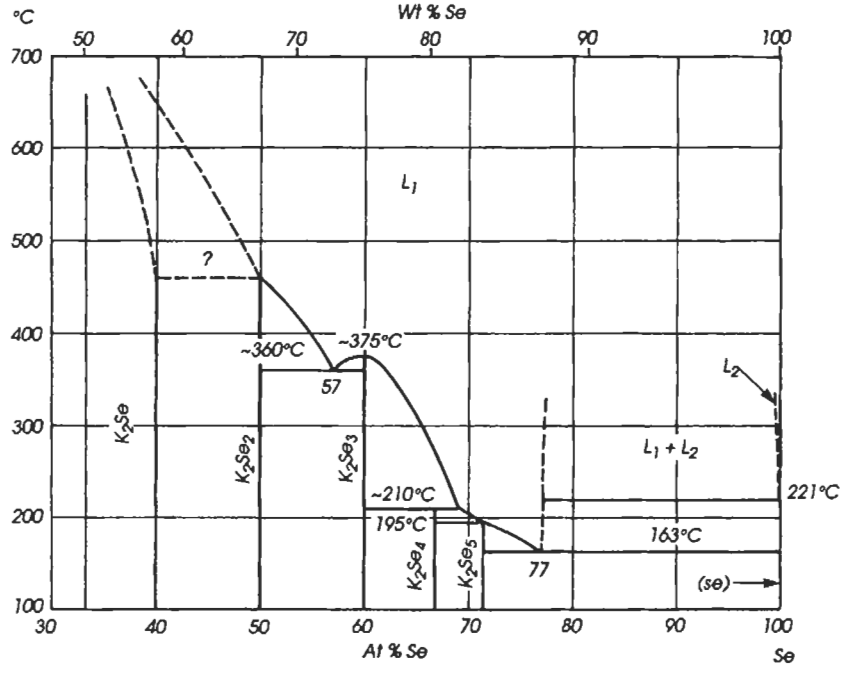
K–S



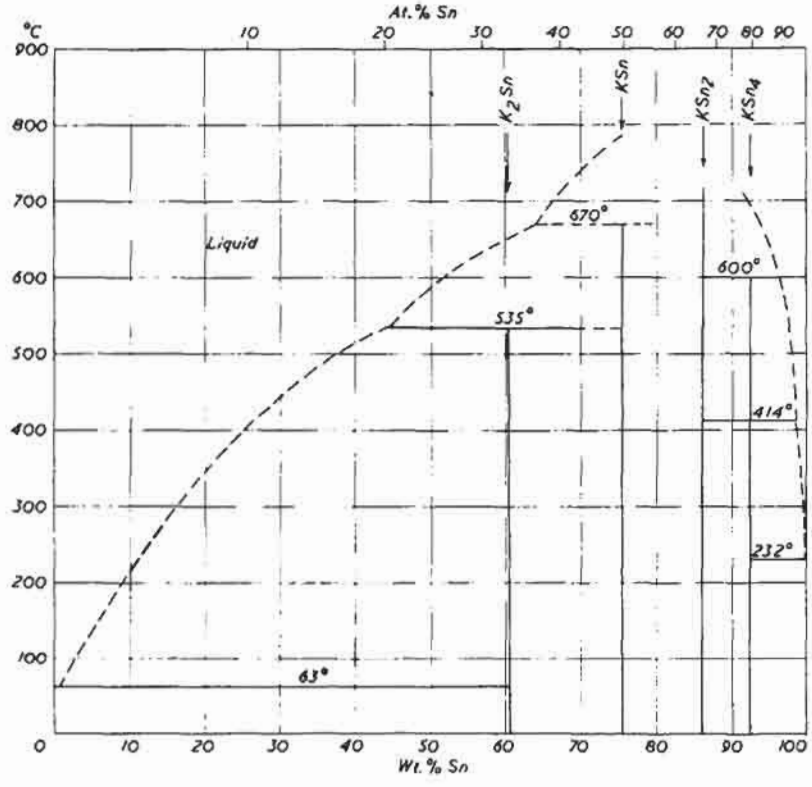
K–Sb


°C
At.% Sb
10 20 30 40 50 70 90
900
800
700
600
500
400
300
200
100
0
K_3Sb
812°
KSb
Liquid
Liquid
605°
630·5°
485°
400°
63°
63·5°
10 20 30 40 50 60 70 80 90 100
Wt.% Sb

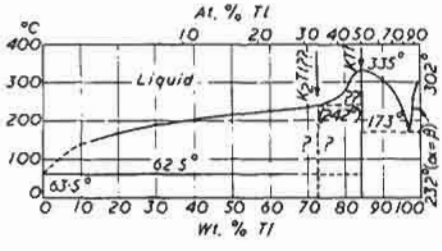
K–Se


°C
Wt % Se
50 60 70 80 90 100
700
600
500
400
300
200
100
L_1
?
~360°C
~375°C
57
L_2
K_2Se
K_2Se_2
K_2Se_3
$L_1 + L_2$
221°C
~210°C
195°C
163°C
K_2Se_4
K_2Se_5
77
(se)
30 40 50 60 70 80 90 100
At % Se
Se

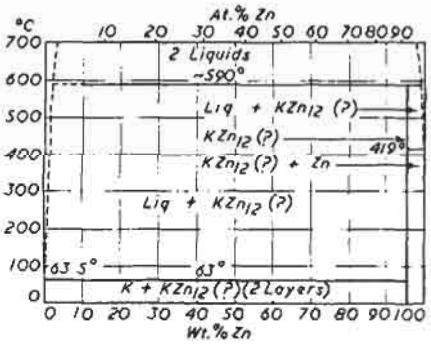
K–Sn

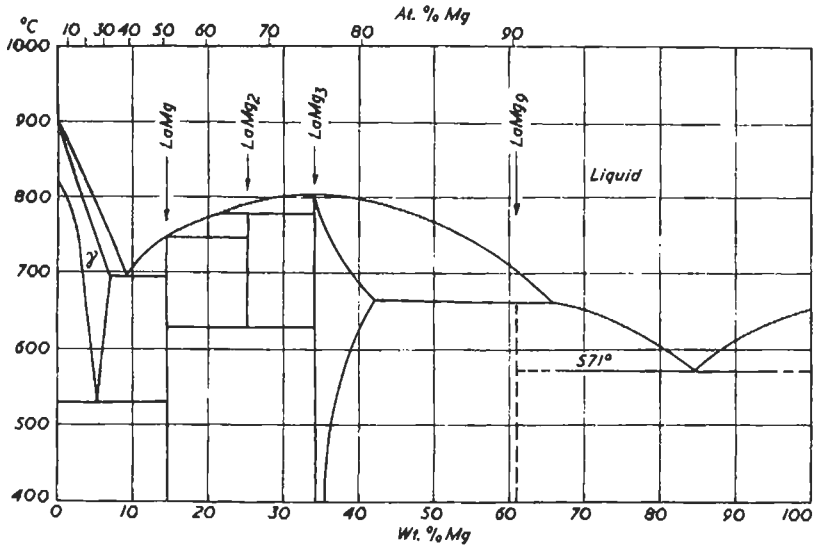

At.% Sn
°C
10 20 30 40 50 60 70 80 90
900
800
700
600
500
400
300
200
100
0
K_2Sn
KSn
KSn_2
KSn_4
Liquid
670°
600°
535°
414°
232°
63°
0 10 20 30 40 50 60 70 80 90 100
Wt.% Sn

K–Tl

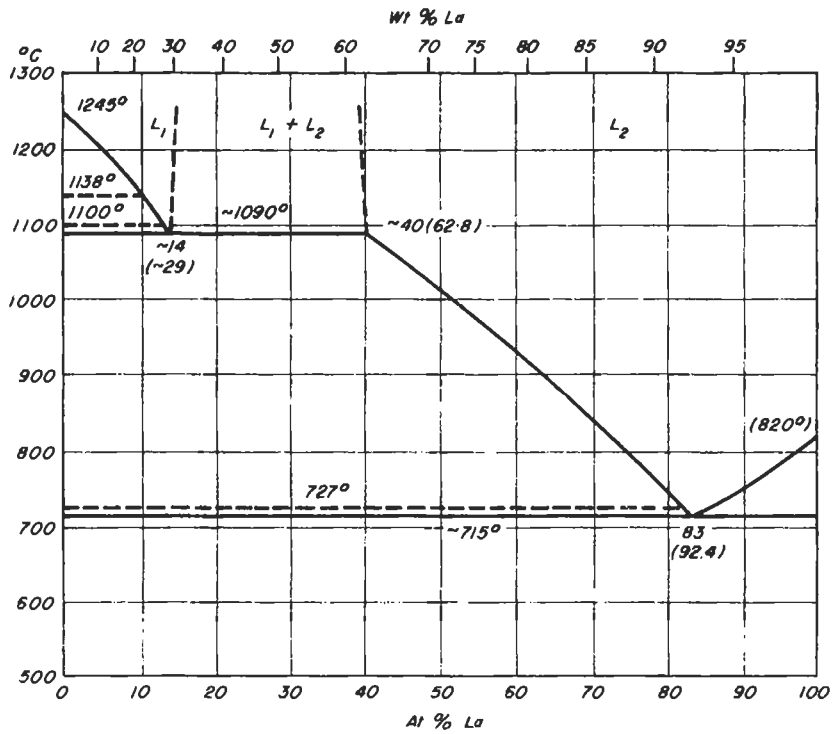

At. % Tl
°C
10 20 30 40 50 70 90
400
300
200
100
0
Liquid
K_2Tl_{22}
KTl
335°
302°
242°
173°
232°(α=β)
62.5°
63.5°
0 10 20 30 40 50 60 70 80 90 100
Wt. % Tl

K–Zn


At.% Zn
°C
10 20 30 40 50 60 70 80 90
700
600
500
400
300
200
100
0
2 Liquids
~590°
Liq + KZn_{12} (?)
KZn_{12} (?)
KZn_{12} (?) + Zn
419°
Liq + KZn_{12} (?)
63.5°
63°
K + KZn_{12} (?) (2 Layers)
0 10 20 30 40 50 60 70 80 90 100
Wt.% Zn

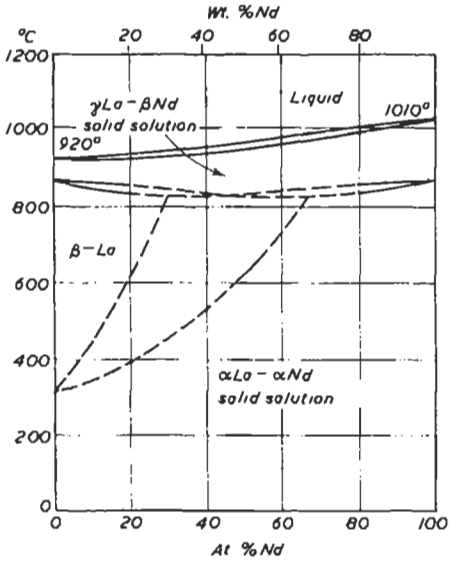

°C
At. % Mg
LaMg
LaMg2
LaMg3
LaMg9
Liquid
γ
571°
Wt. % Mg

La–Mg

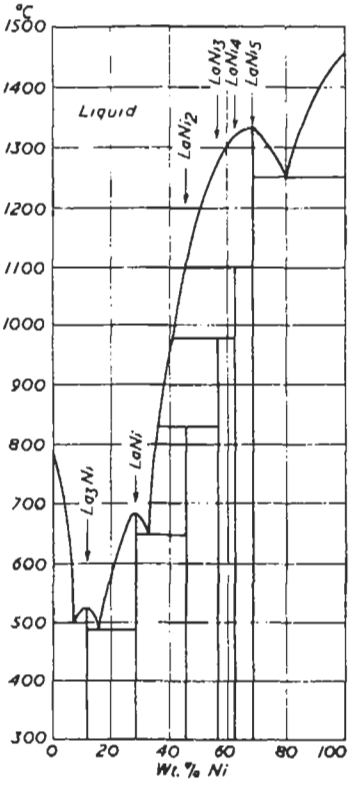

Wt % La
°C
1245°
L1
L1 + L2
L2
1138°
1100°
~1090°
~40(62·8)
~14
(~29)
(820°)
727°
~715°
83
(92.4)
At % La

La–Mn

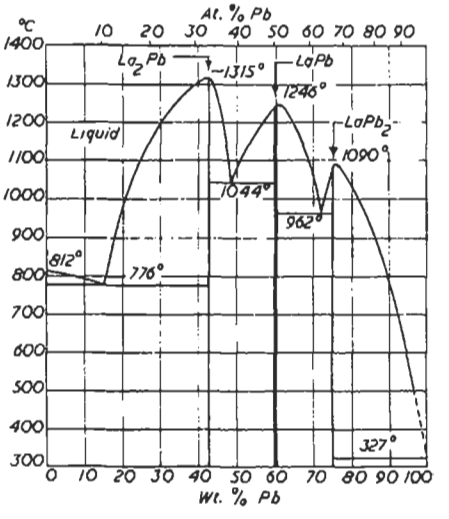
La–Nd



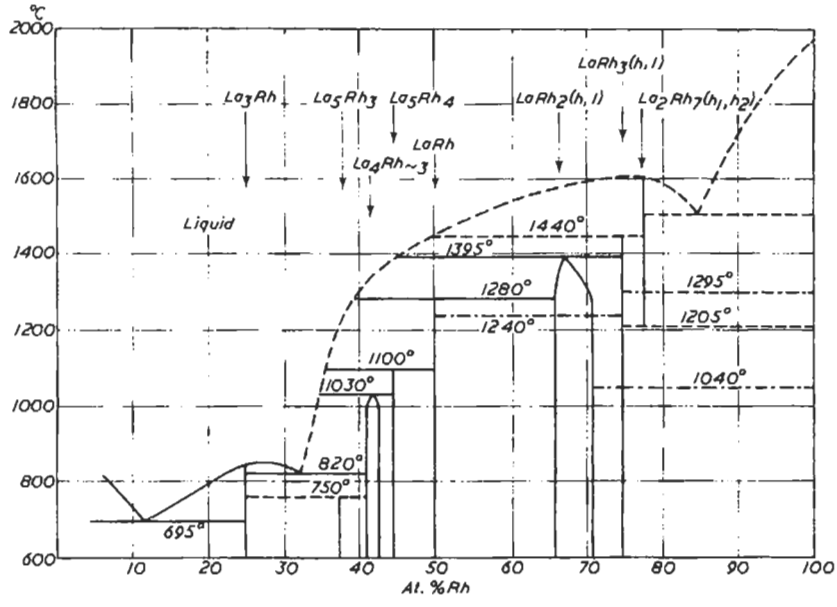
La–Ni



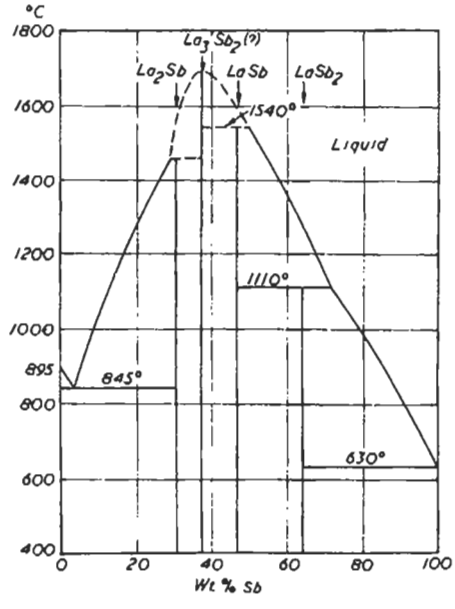
La–Pb



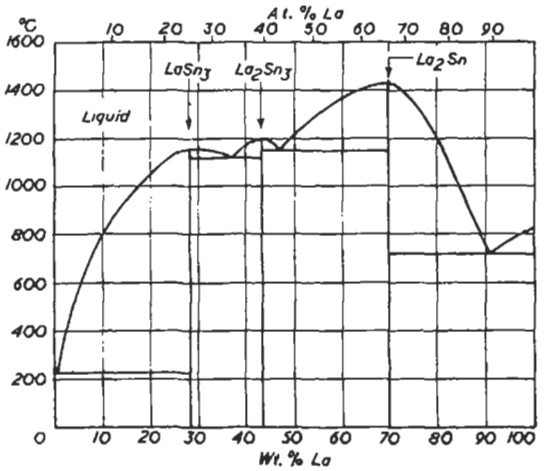
La–Rh


°C
2000
1800
1600
1400
1200
1000
800
600
La3Rh
La5Rh3
La5Rh4
LaRh
La4Rh~3
LaRh2(h, l)
LaRh3(h, l)
La2Rh7(h1, h2)
Liquid
1440°
1395°
1280°
1240°
1295°
1205°
1040°
1100°
1030°
820°
750°
695°
10
20
30
40
50
60
70
80
90
100
At. %Rh

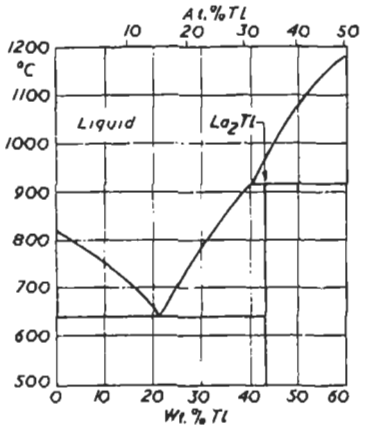
La–Sb


°C
1800
1600
1400
1200
1000
895
800
600
400
La3Sb2(?)
La2Sb
LaSb
LaSb2
1540°
Liquid
1110°
845°
630°
0
20
40
60
80
100
Wt % Sb

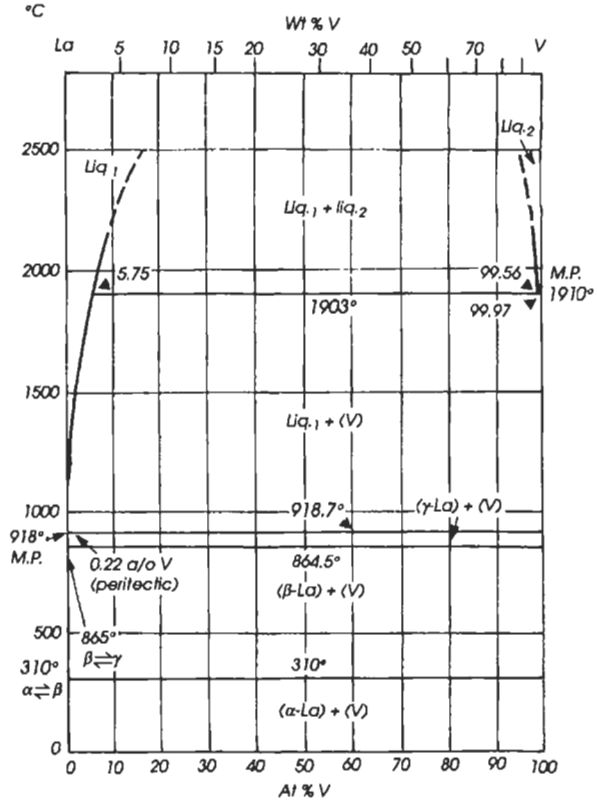
La–Sn


°C
At. % La
Liquid
LaSn3
La2Sn3
La2Sn
Wt. % La

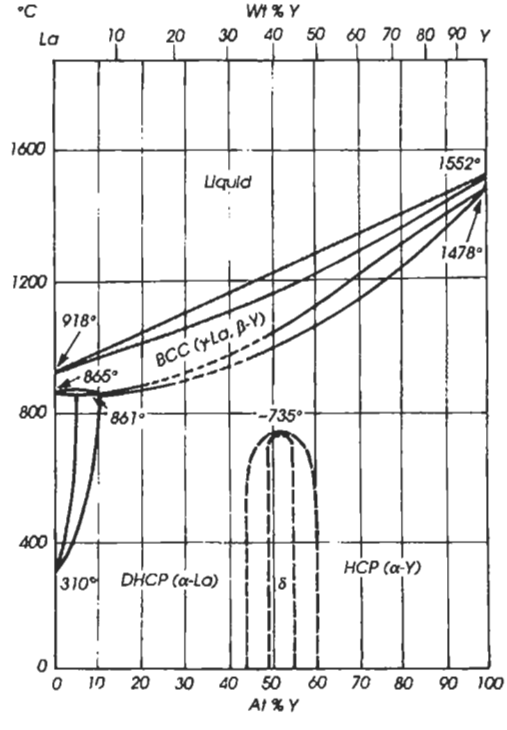
La–Tl


At. % Tl
°C
Liquid
La2Tl
Wt. % Tl

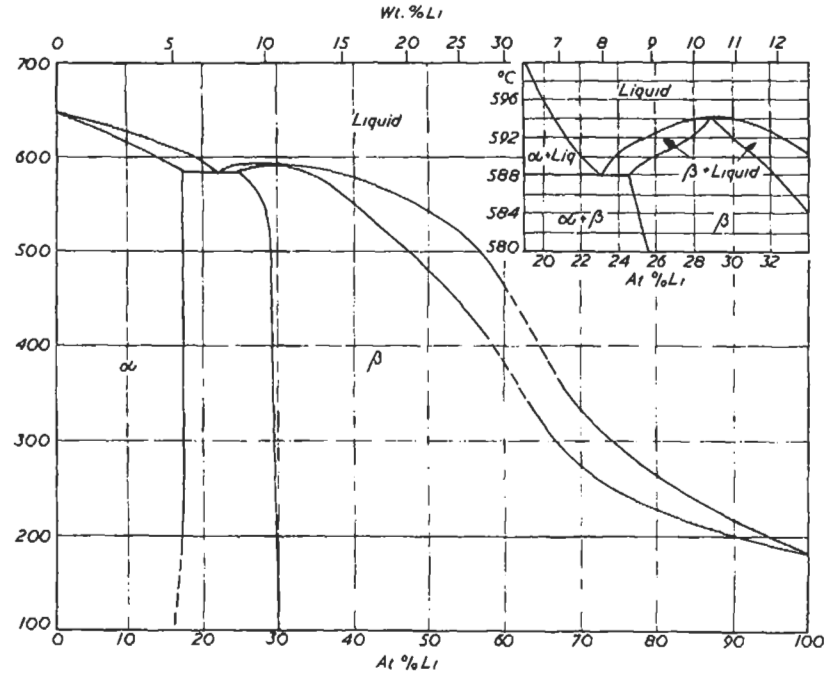
La–V


°C
Wt % V
La
V
Liq.1
Liq.2
Liq.1 + liq.2
5.75
99.56
M.P.
1910°
1903°
99.97
Liq.1 + (V)
918.7°
(γ-La) + (V)
918°
M.P.
0.22 a/o V
(peritectic)
864.5°
(β-La) + (V)
865°
β⇌γ
310°
310°
α⇌β
(α-La) + (V)
At % V

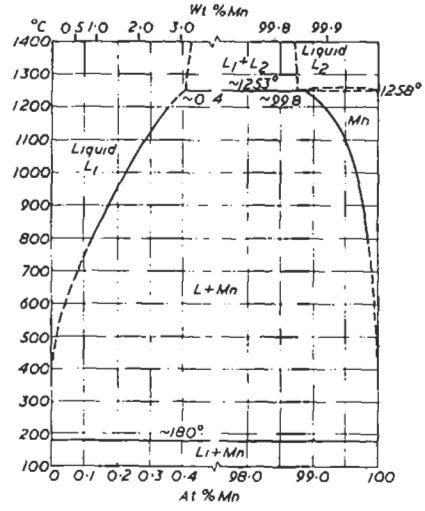
La–Y


°C
Wt % Y
La
Y
Liquid
1552°
1478°
918°
BCC (γ-La, β-Y)
865°
861°
~735°
δ
310°
DHCP (α-La)
HCP (α-Y)
At % Y

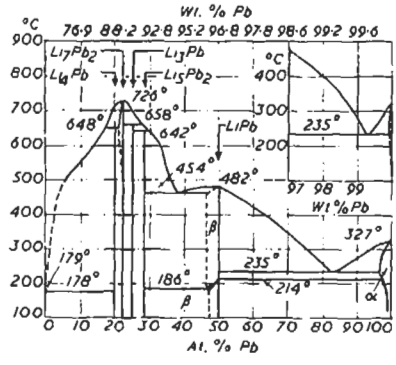
Li–Mg



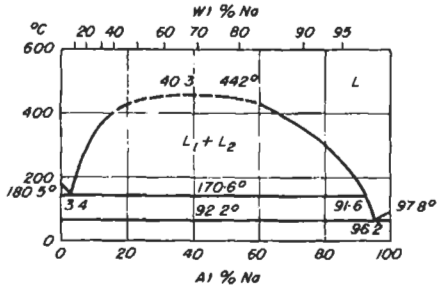
Li–Mn



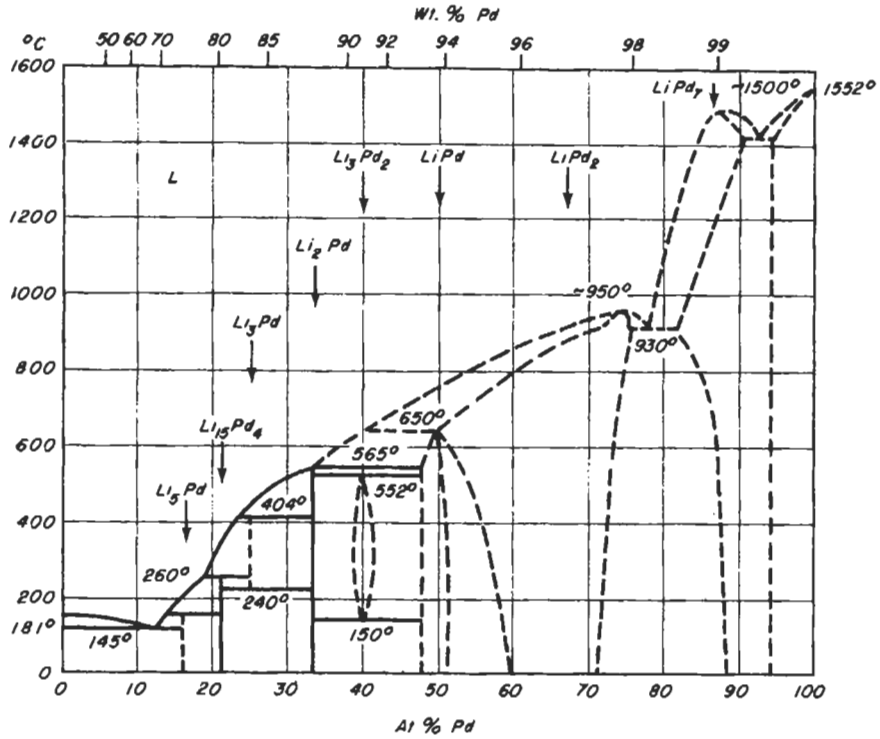
Li–Pb



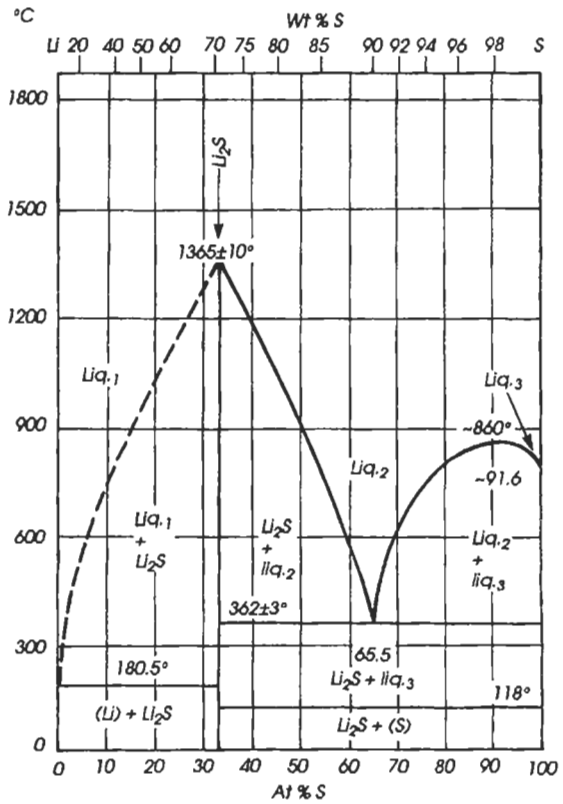
Li–Na



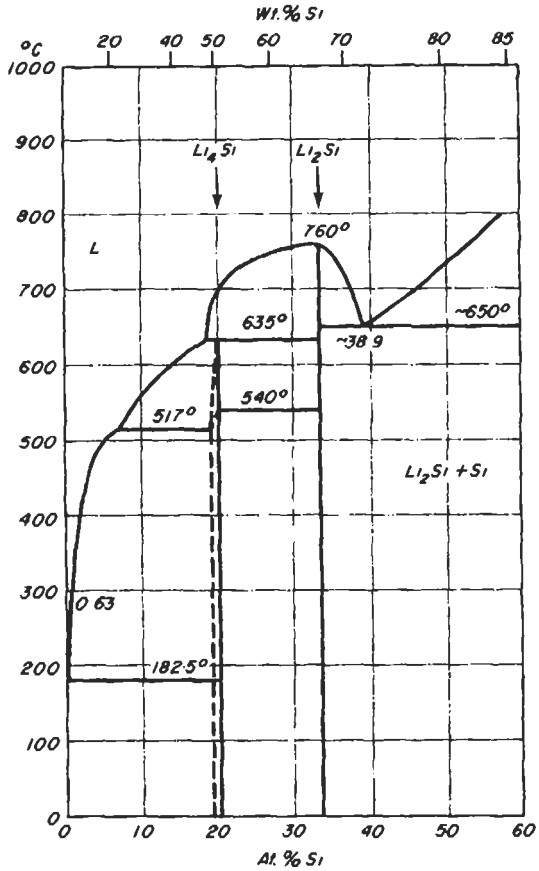
Li-Pd


Wt. % Pd
°C
50 60 70 80 85 90 92 94 96 98 99
1600
1400
1200
1000
800
600
400
200
181°
0
L
Li3Pd2
LiPd
LiPd2
LiPd7
~1500°
1552°
Li2Pd
~950°
930°
Li3Pd
Li15Pd4
650°
565°
Li5Pd
552°
404°
260°
240°
150°
145°
0 10 20 30 40 50 60 70 80 90 100
At % Pd

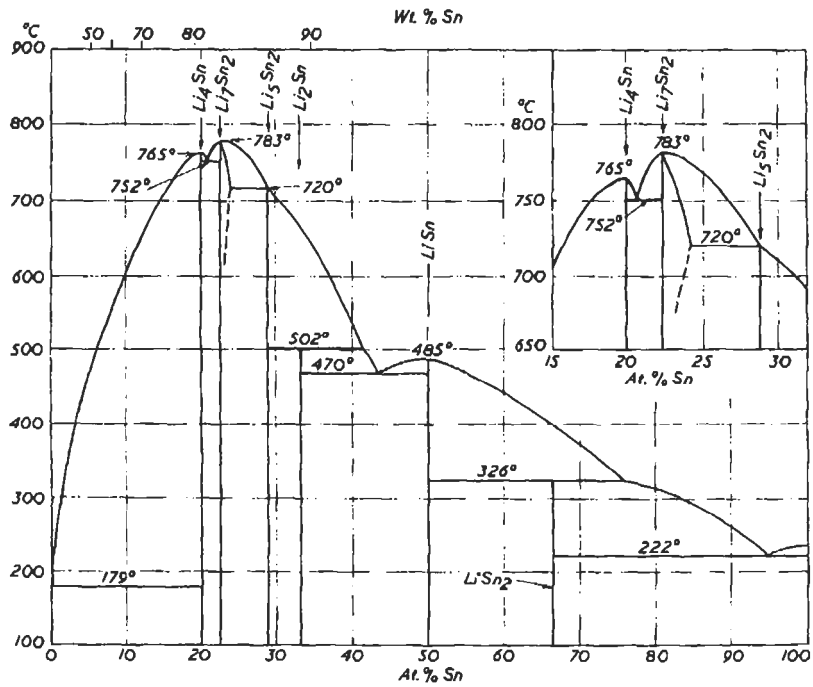
Li-S

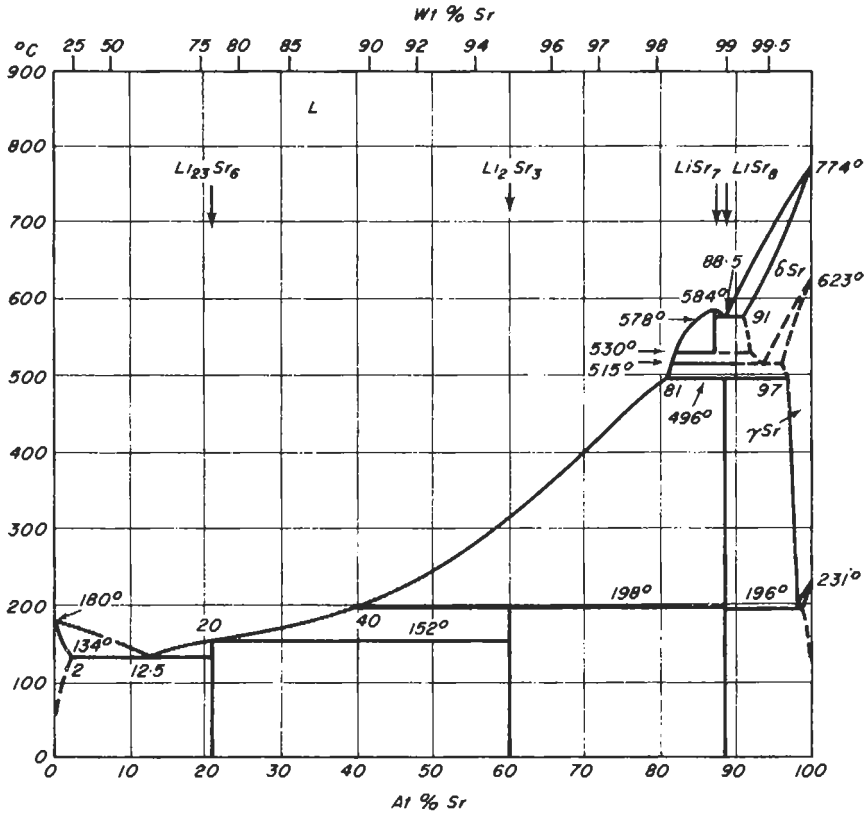

°C
Wt % S
Li 20 40 50 60 70 75 80 85 90 92 94 96 98 S
1800
1500
1200
900
600
300
0
Li2S
1365±10°
Liq.1
Liq.3
~860°
Liq.2
~91.6
Liq.1 + Li2S
Li2S + liq.2
362±3°
Liq.2 + liq.3
180.5°
65.5
Li2S + liq.3
118°
(Li) + Li2S
Li2S + (S)
0 10 20 30 40 50 60 70 80 90 100
At % S

Li–Si


Wt. % Si
°C
20 40 50 60 70 80 85
1000
900
800
700
600
500
400
300
200
100
0
Li_4Si
Li_2Si
760°
L
635°
~650°
~38 9
540°
517°
$Li_2Si + Si$
0 63
182·5°
0 10 20 30 40 50 60
At. % Si

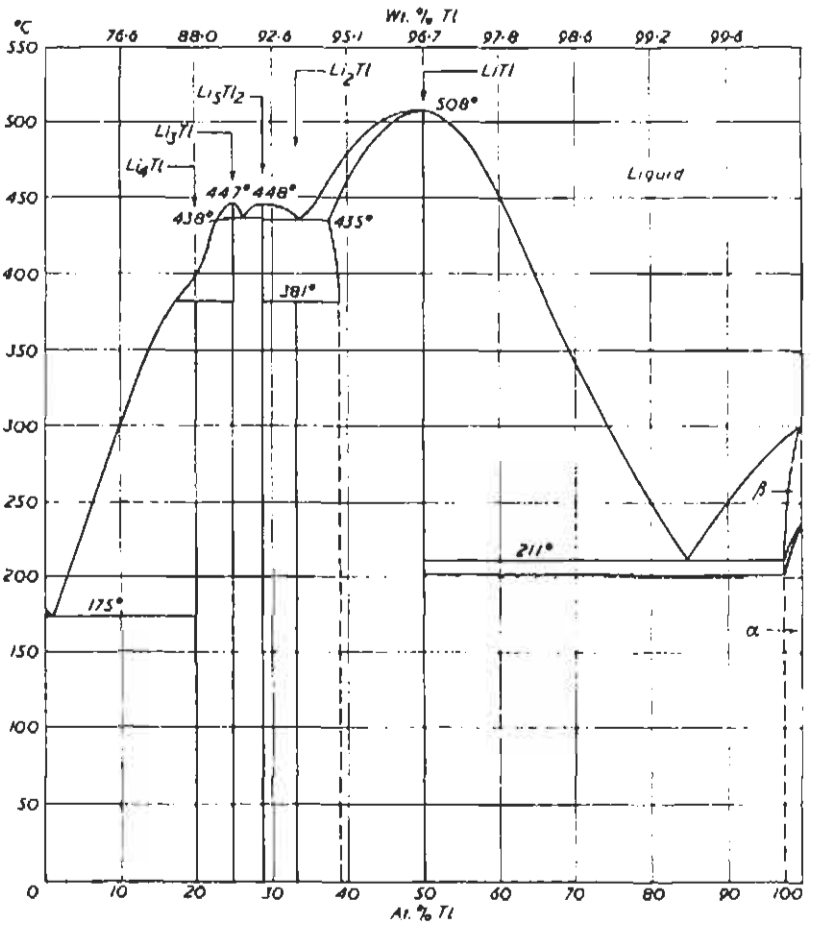
Li–Sn


Wt. % Sn
°C
50 70 80 90
900
800
700
600
500
400
300
200
100
Li_4Sn
Li_7Sn_2
Li_5Sn_2
Li_2Sn
765°
752°
783°
720°
LiSn
502°
470°
485°
326°
222°
179°
$LiSn_2$
0 10 20 30 40 50 60 70 80 90 100
At. % Sn
°C
800
750
700
650
15 20 25 30
At. % Sn

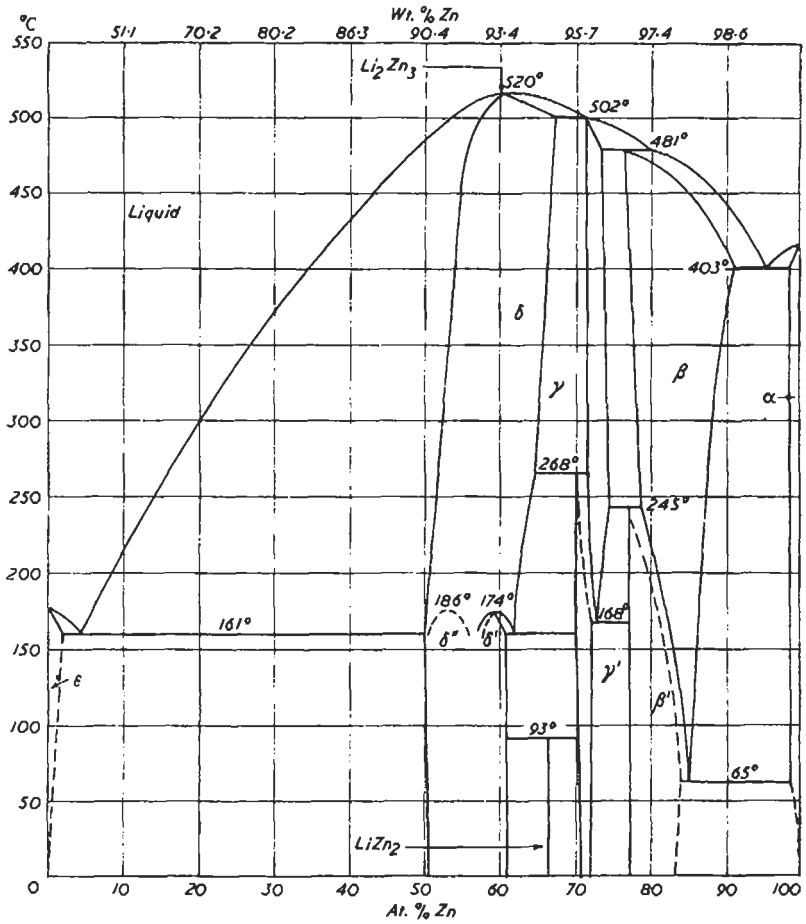

Wt % Sr
°C
25 50 75 80 85 90 92 94 96 97 98 99 99·5
900
800
700
600
500
400
300
200
100
0
L
$Li_{23}Sr_6$
Li_2Sr_3
$LiSr_7$
$LiSr_8$
774°
88·5
δSr
623°
584°
578°
91
530°
515°
81
97
496°
γSr
180°
134°
2
12·5
20
40
152°
198°
196°
231°
0 10 20 30 40 50 60 70 80 90 100
At % Sr

Li–Sr

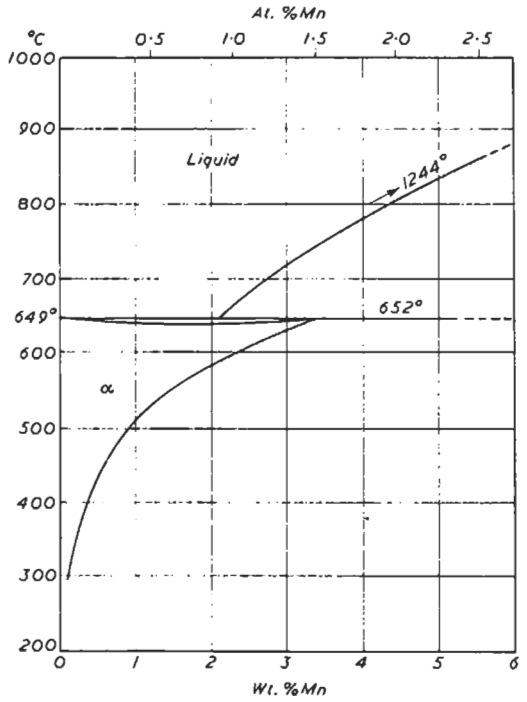
Li–Tl


°C
Wt. % Tl
76·6
88·0
92·6
95·1
96·7
97·8
98·6
99·2
99·6
550
500
450
400
350
300
250
200
150
100
50
0
Li_5Tl_2
Li_2Tl
LiTl
Li_3Tl
Li_4Tl
508°
Liquid
447°
448°
438°
435°
381°
β
211°
175°
α
10
20
30
40
50
60
70
80
90
100
At. % Tl

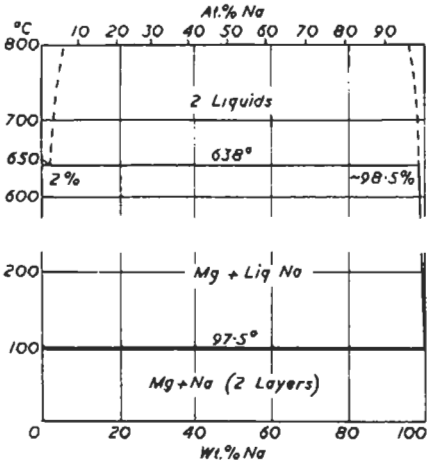
Li–Zn


°C
Wt. % Zn
51·1
70·2
80·2
86·3
90·4
93·4
95·7
97·4
98·6
550
500
450
400
350
300
250
200
150
100
50
0
Li_2Zn_3
520°
502°
481°
403°
Liquid
δ
γ
β
α
268°
245°
186°
174°
168°
161°
δ''
δ'
γ'
β'
ε
93°
65°
$LiZn_2$
10
20
30
40
50
60
70
80
90
100
At. % Zn

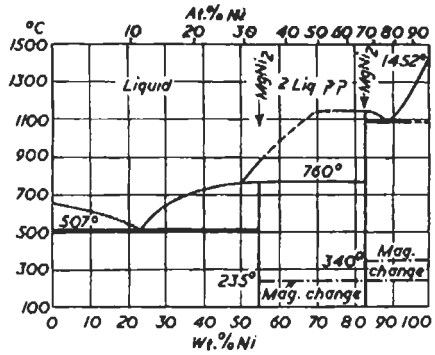
Mg–Mn


At. %Mn
°C
0·5
1·0
1·5
2·0
2·5
1000
900
800
700
649°
600
500
400
300
200
Liquid
1244°
652°
α
0
1
2
3
4
5
6
Wt. %Mn

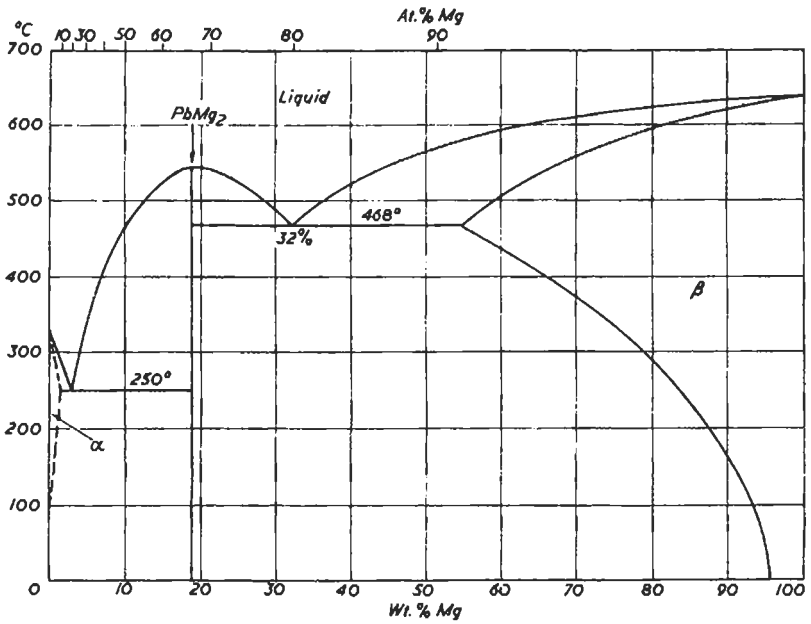
Mg–Na


At.% Na
°C
10
20
30
40
50
60
70
80
90
800
700
650
600
2 Liquids
638°
2%
~98·5%
200
100
Mg + Liq Na
97·5°
Mg+Na (2 Layers)
0
20
40
60
80
100
Wt.% Na

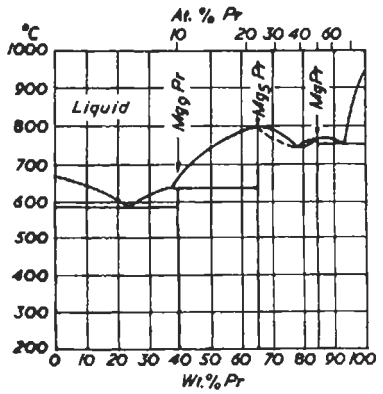
Mg–Ni



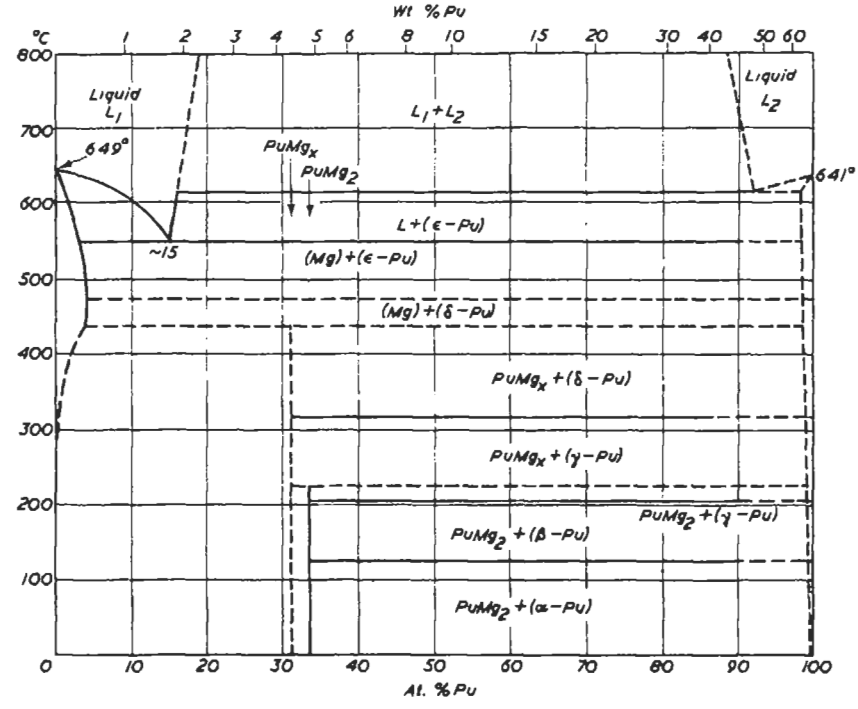
Mg–Pb



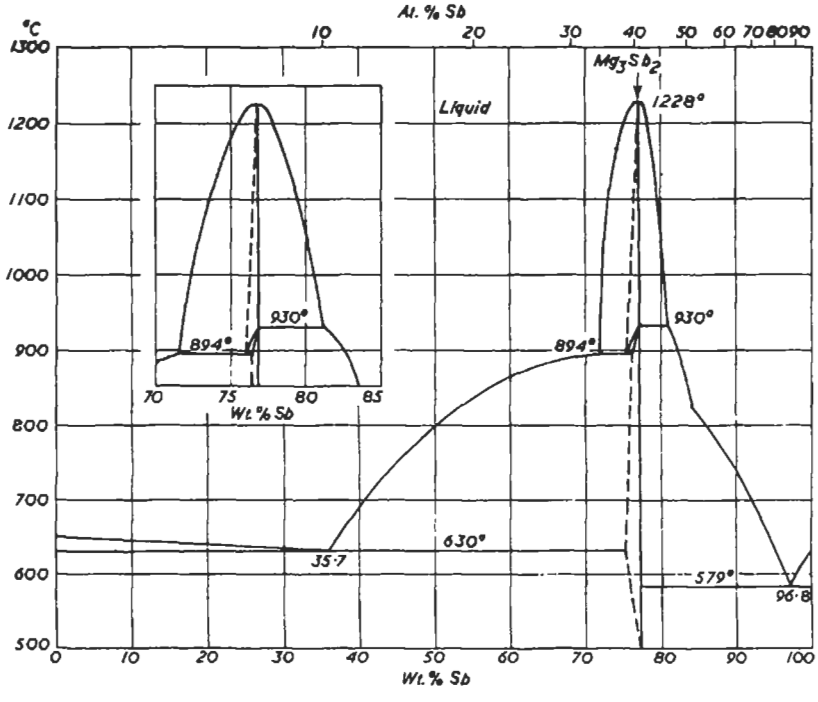
Mg–Pr



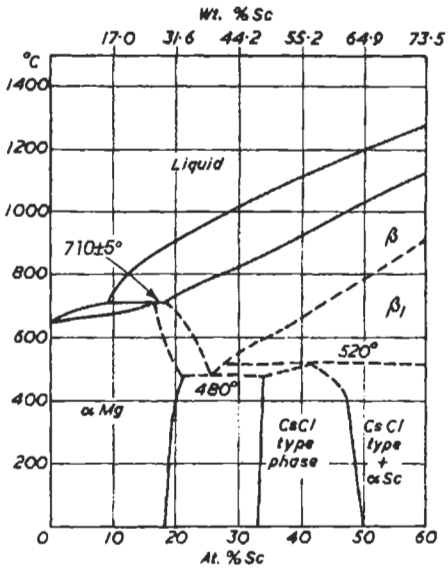
Mg–Pu


Wt % Pu
°C
1 2 3 4 5 6 8 10 15 20 30 40 50 60
800
700
600
500
400
300
200
100
0
Liquid L1
L1+L2
Liquid L2
649°
PuMgx
PuMg2
641°
~15
L+(ε−Pu)
(Mg)+(ε−Pu)
(Mg)+(δ−Pu)
PuMgx+(δ−Pu)
PuMgx+(γ−Pu)
PuMg2+(γ−Pu)
PuMg2+(β−Pu)
PuMg2+(α−Pu)
10 20 30 40 50 60 70 80 90 100
At. % Pu

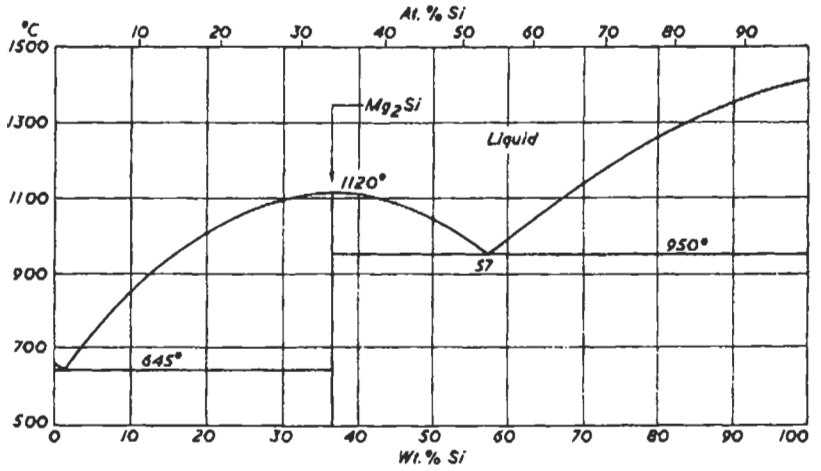
Mg–Sb


At. % Sb
°C
10 20 30 40 50 60 70 80 90
1300
1200
1100
1000
900
800
700
600
500
Mg3Sb2
1228°
Liquid
930°
894°
930°
894°
630°
35·7
579°
96·8
70 75 80 85
Wt % Sb
0 10 20 30 40 50 60 70 80 90 100
Wt. % Sb

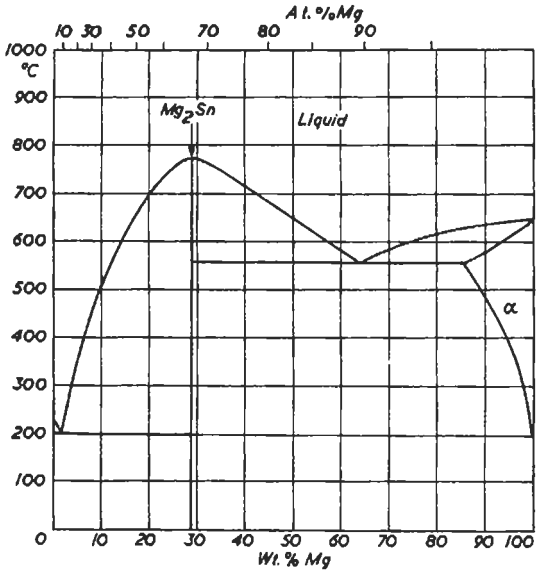
Mg–Sc


Wt. % Sc
17·0
31·6
44·2
55·2
64·9
73·5
°C
1400
1200
1000
800
600
400
200
Liquid
710±5°
β
β1
520°
480°
α Mg
CsCl type phase
Cs Cl type + α Sc
0
10
20
30
40
50
60
At. % Sc

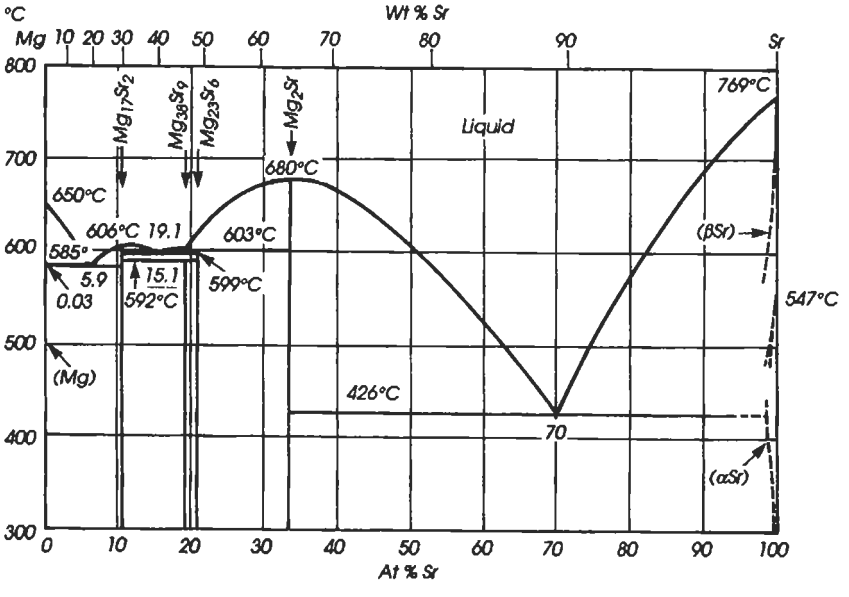
Mg–Si


At. % Si
°C
10
20
30
40
50
60
70
80
90
1500
1300
1100
900
700
500
Mg2Si
Liquid
1120°
950°
57
645°
0
10
20
30
40
50
60
70
80
90
100
Wt. % Si

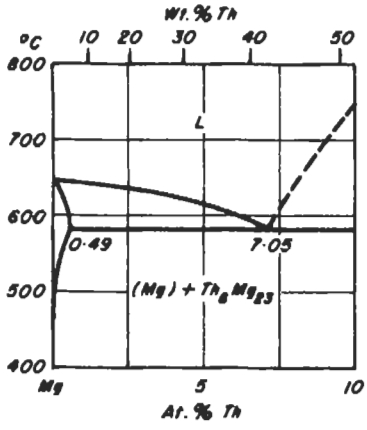
Mg–Sn


At.%Mg
10 30 50 70 80 90
1000
°C
900
800
700
600
500
400
300
200
100
0
Mg_2Sn
Liquid
α
10 20 30 40 50 60 70 80 90 100
Wt.% Mg

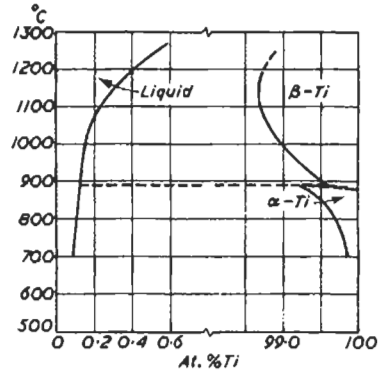
Mg–Sr


°C
Wt % Sr
Mg 10 20 30 40 50 60 70 80 90 Sr
800
700
600
500
400
300
$Mg_{17}Sr_2$
$Mg_{38}Sr_9$
$Mg_{23}Sr_6$
Mg_2Sr
Liquid
769°C
680°C
650°C
606°C 19.1
603°C
585°
5.9
0.03
15.1
592°C
599°C
(βSr)
547°C
(Mg)
426°C
70
(αSr)
0 10 20 30 40 50 60 70 80 90 100
At % Sr

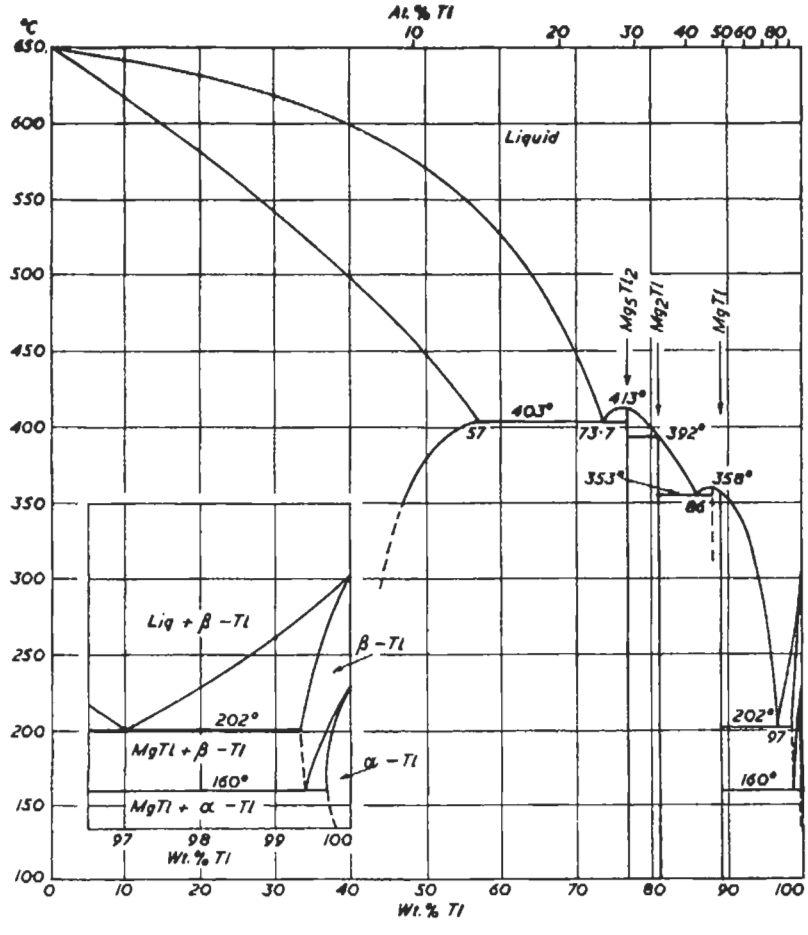
Mg–Th



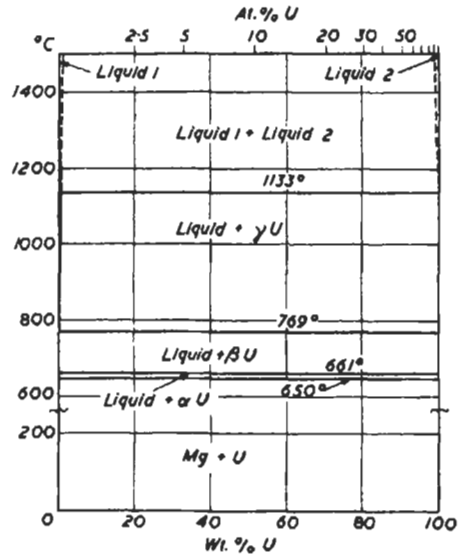
Mg–Ti



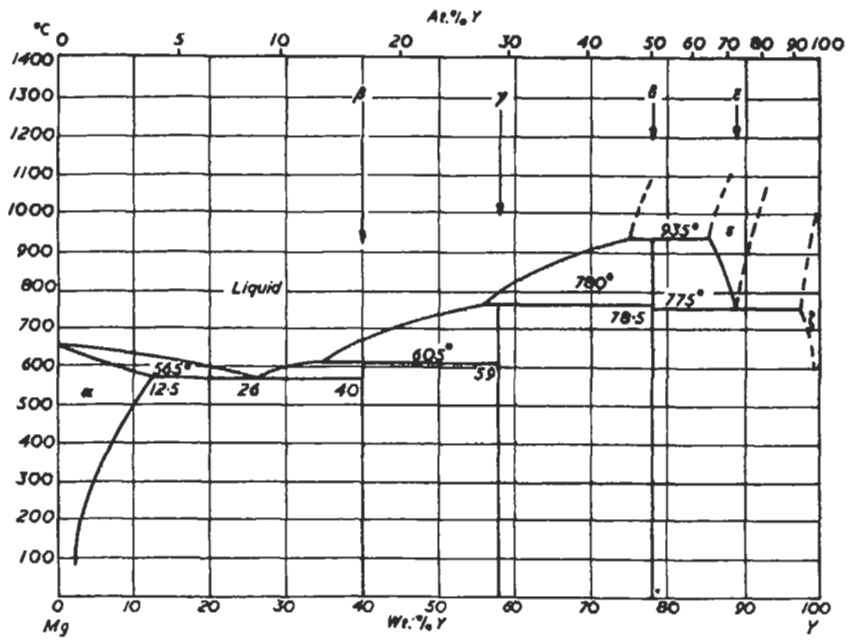
Mg–Tl

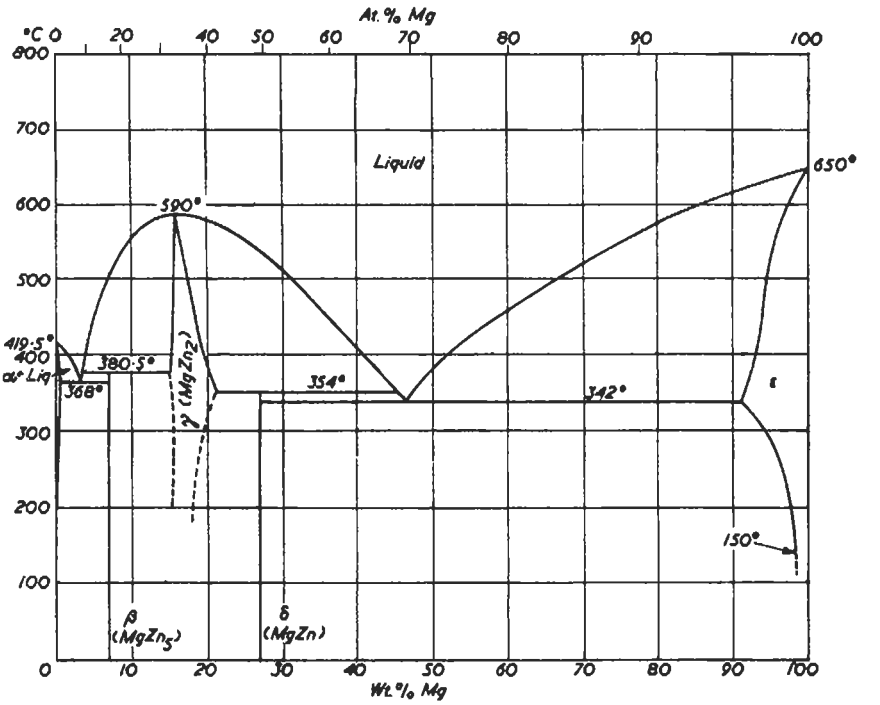


Mg–U

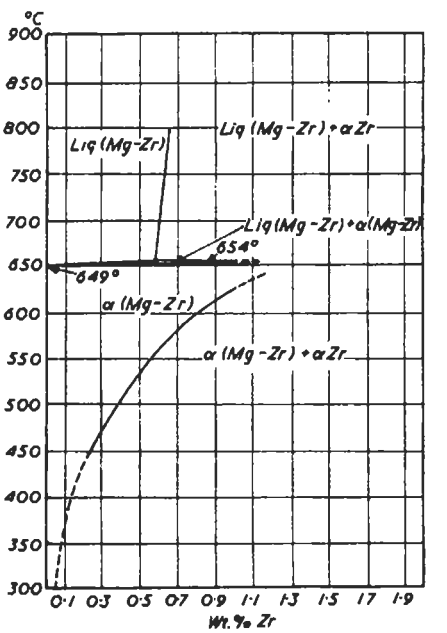

At.% U
°C
2·5
5
10
20
30
50
Liquid 1
Liquid 2
1400
Liquid 1 + Liquid 2
1200
1133°
Liquid + γ U
1000
800
769°
Liquid + β U
661°
600
Liquid + α U
650°
200
Mg + U
0
20
40
60
80
100
Wt. % U

Mg–Y

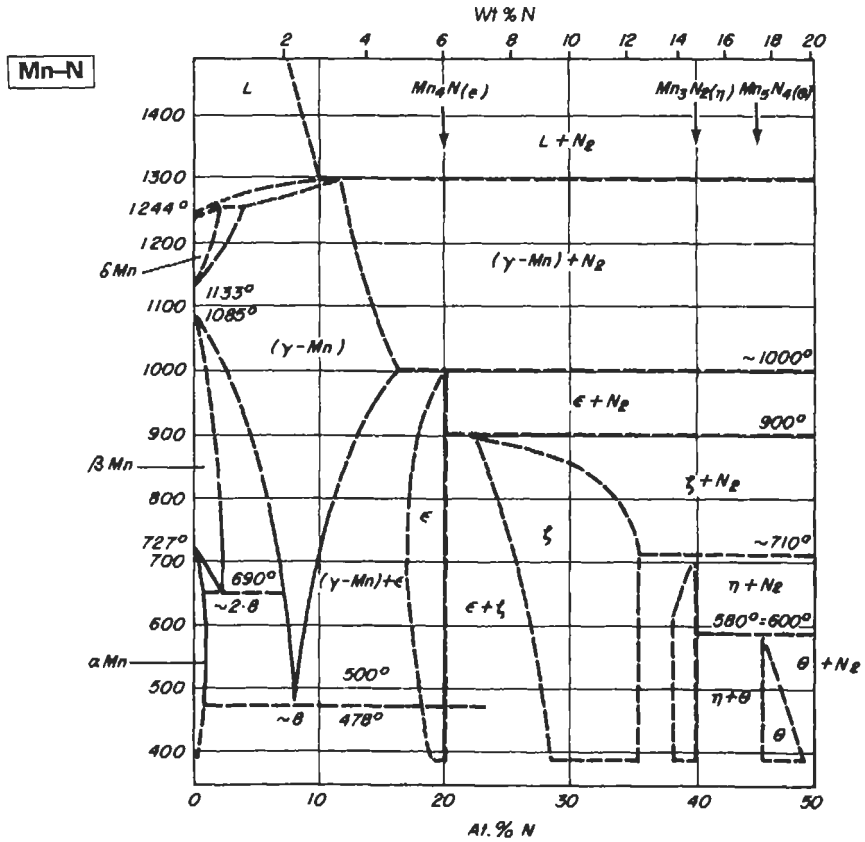

At.% Y
°C
0
5
10
20
30
40
50
60
70
80
90
100
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
β
γ
δ
ε
835°
Liquid
780°
775°
785
605°
565°
12·5
26
40
59
α
0
10
20
30
40
50
60
70
80
90
100
Mg
Wt.% Y
Y


At. % Mg
°C 0 20 40 50 60 70 80 90 100
800
700
600
500
419·5°
400
α + Liq
380·5°
368°
γ (MgZn2)
590°
Liquid
354°
342°
650°
ε
150°
300
200
100
0
β (MgZn5)
δ (MgZn)
10 20 30 40 50 60 70 80 90 100
Wt. % Mg

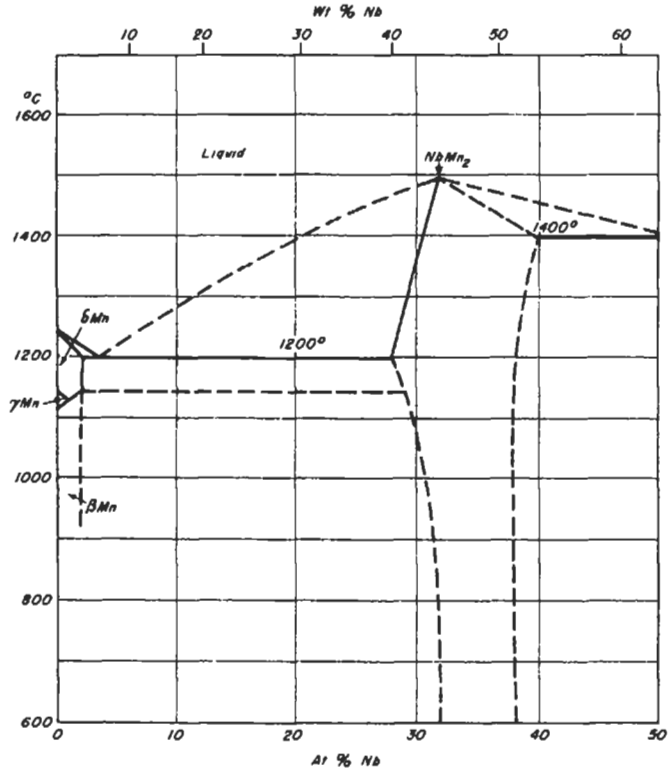
Mg–Zn


°C
900
850
800
750
700
650
600
550
500
450
400
350
300
Liq (Mg-Zr)
Liq (Mg-Zr) + α Zr
Liq (Mg-Zr) + α (Mg-Zr)
654°
649°
α (Mg-Zr)
α (Mg-Zr) + α Zr
0·1 0·3 0·5 0·7 0·9 1·1 1·3 1·5 1·7 1·9
Wt. % Zr

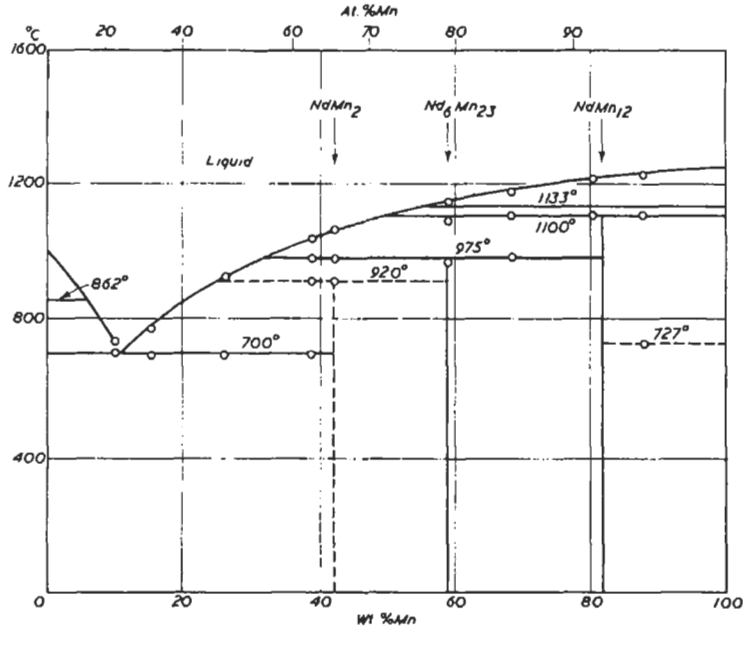
Mg–Zr


Mn–N
Wt % N
2
4
6
8
10
12
14
16
18
20
L
$Mn_4N(\epsilon)$
$Mn_3N_2(\eta)$
$Mn_5N_4(\theta)$
$L+N_2$
1400
1300
1244°
1200
δMn
$(\gamma\text{-}Mn)+N_2$
1133°
1100
1085°
$(\gamma\text{-}Mn)$
~1000°
1000
$\epsilon+N_2$
900°
900
βMn
$\zeta+N_2$
800
ϵ
ζ
727°
~710°
700
690°
$(\gamma\text{-}Mn)+\epsilon$
$\eta+N_2$
~2·8
$\epsilon+\zeta$
580°:600°
600
αMn
$\theta+N_2$
500°
500
$\eta+\theta$
~8
478°
θ
400
0
10
20
30
40
50
At. % N

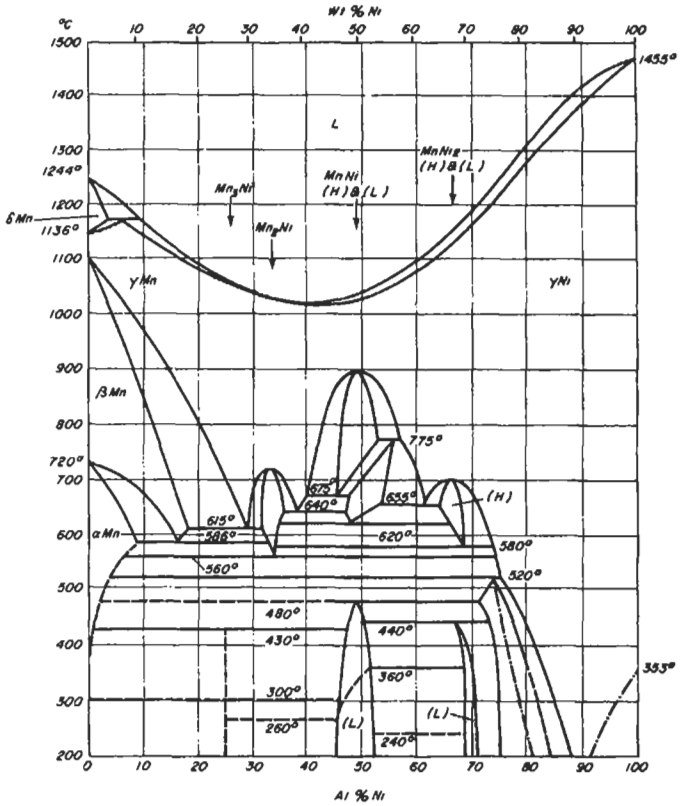
Mn–Nb


Wt % Nb
10
20
30
40
50
60
°C
1600
1400
1200
1000
800
600
Liquid
NbMn2
1400°
1200°
δMn
γMn
βMn
0
10
20
30
40
50
At % Nb

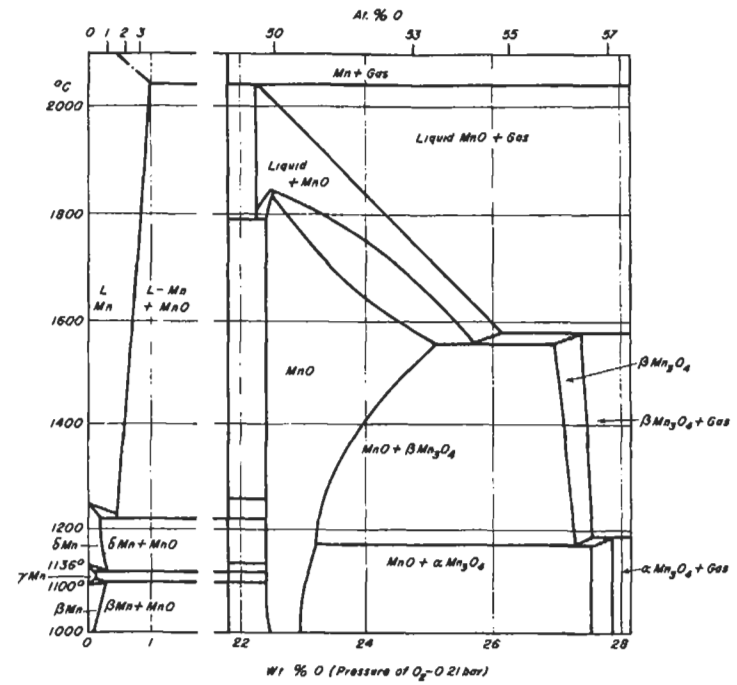
Mn–Nd


At.%Mn
°C
20
40
60
70
80
90
1600
1200
800
400
NdMn2
Nd6Mn23
NdMn12
Liquid
1133°
1100°
975°
920°
862°
700°
727°
0
20
40
60
80
100
Wt %Mn

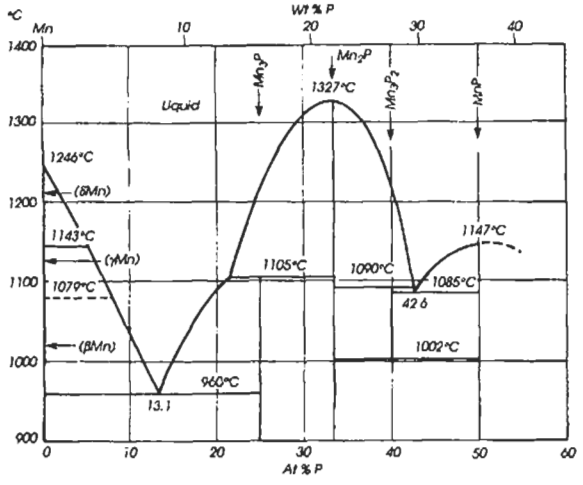
Mn–Ni


Wt % Ni
°C
1500
1400
1300
1244°
1200
δMn
1136°
1100
1000
900
800
720°
700
600
500
400
300
200
1455°
L
MnNi₂
(H)B(L)
Mn₅Ni
MnNi
(H)B(L)
Mn₂Ni
γMn
γNi
βMn
775°
675°
640°
635°
(H)
615°
αMn
586°
620°
580°
560°
520°
480°
430°
440°
360°
353°
300°
260°
(L)
(L)
240°
0 10 20 30 40 50 60 70 80 90 100
At % Ni

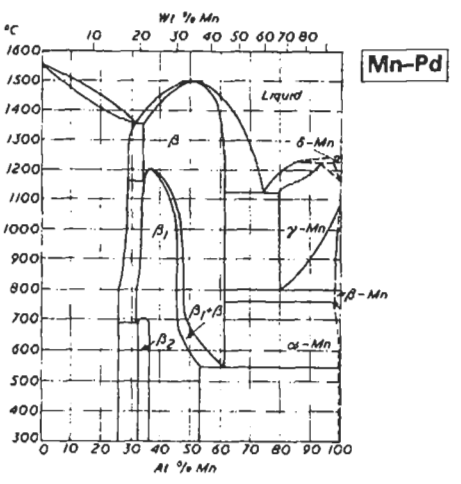
Mn–O


At. % O
0 1 2 3
50
33
55
57
°C
2000
1800
1600
1400
1200
δMn
1136°
γMn
1100°
βMn
1000
Mn + Gas
Liquid MnO + Gas
Liquid
+ MnO
L
Mn
L – Mn
+ MnO
MnO
βMn₃O₄
βMn₃O₄ + Gas
MnO + βMn₃O₄
δMn + MnO
MnO + αMn₃O₄
αMn₃O₄ + Gas
βMn + MnO
0 1
22 24 26 28
Wt % O (Pressure of O₂ – 0·21 bar)

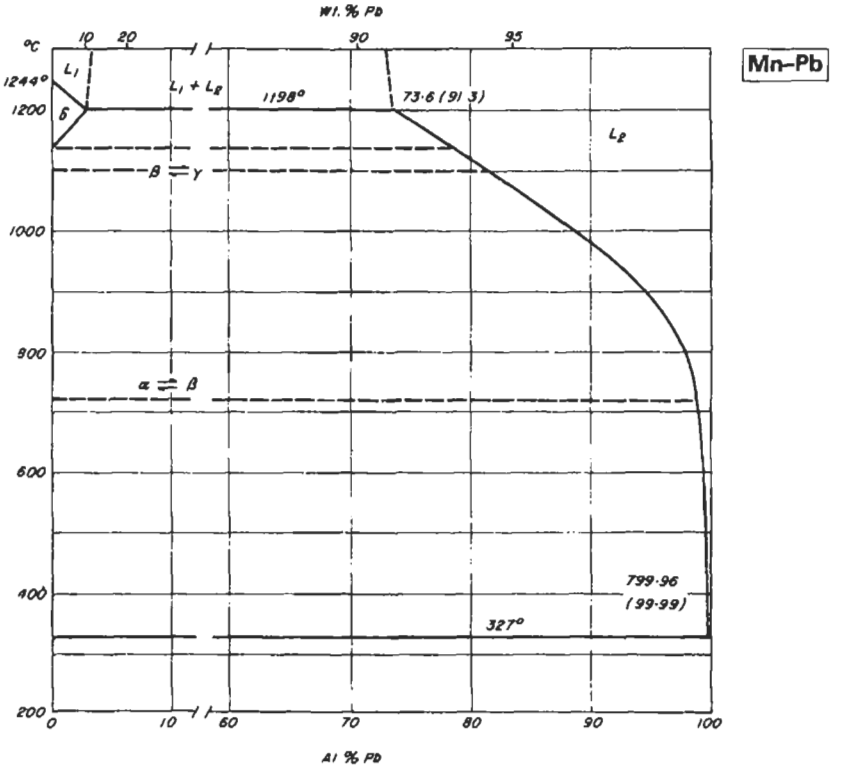
Mn–P



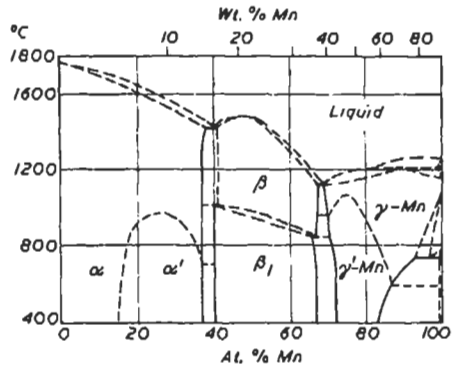
Mn–Pd



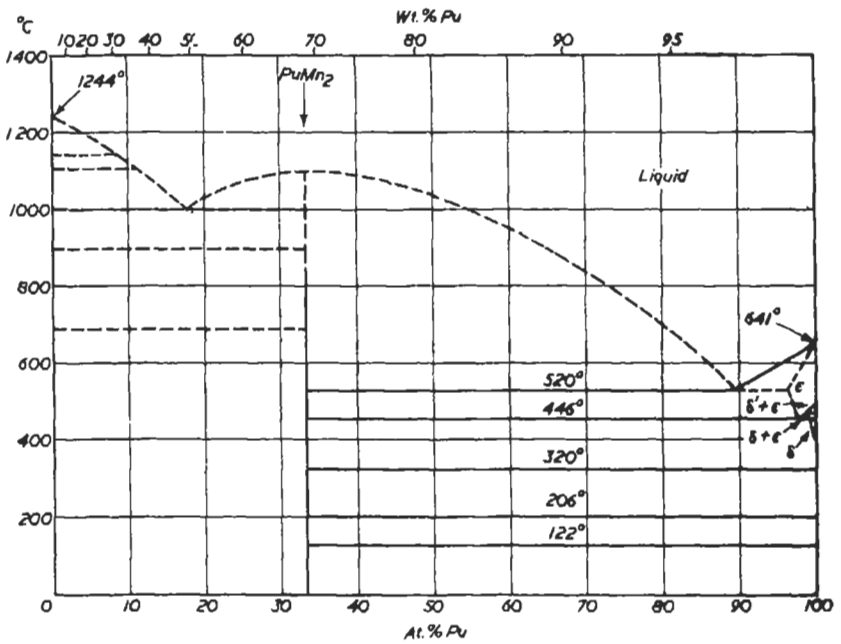
Mn–Pb



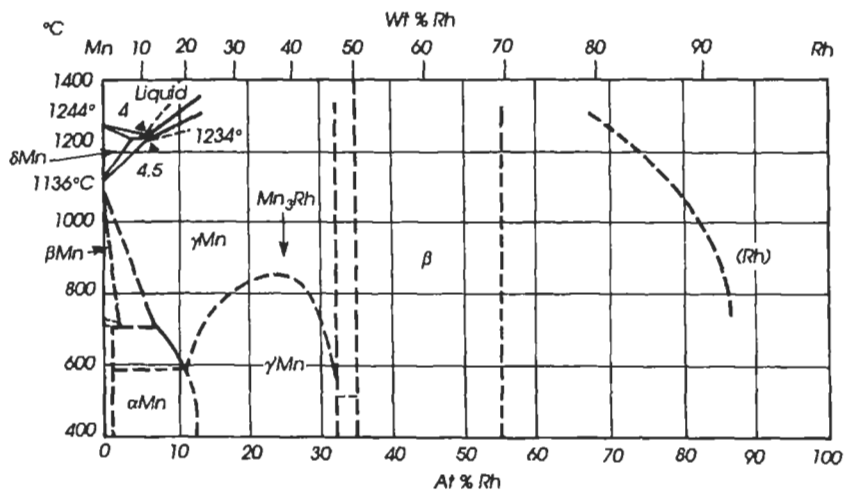
Mn–Pt

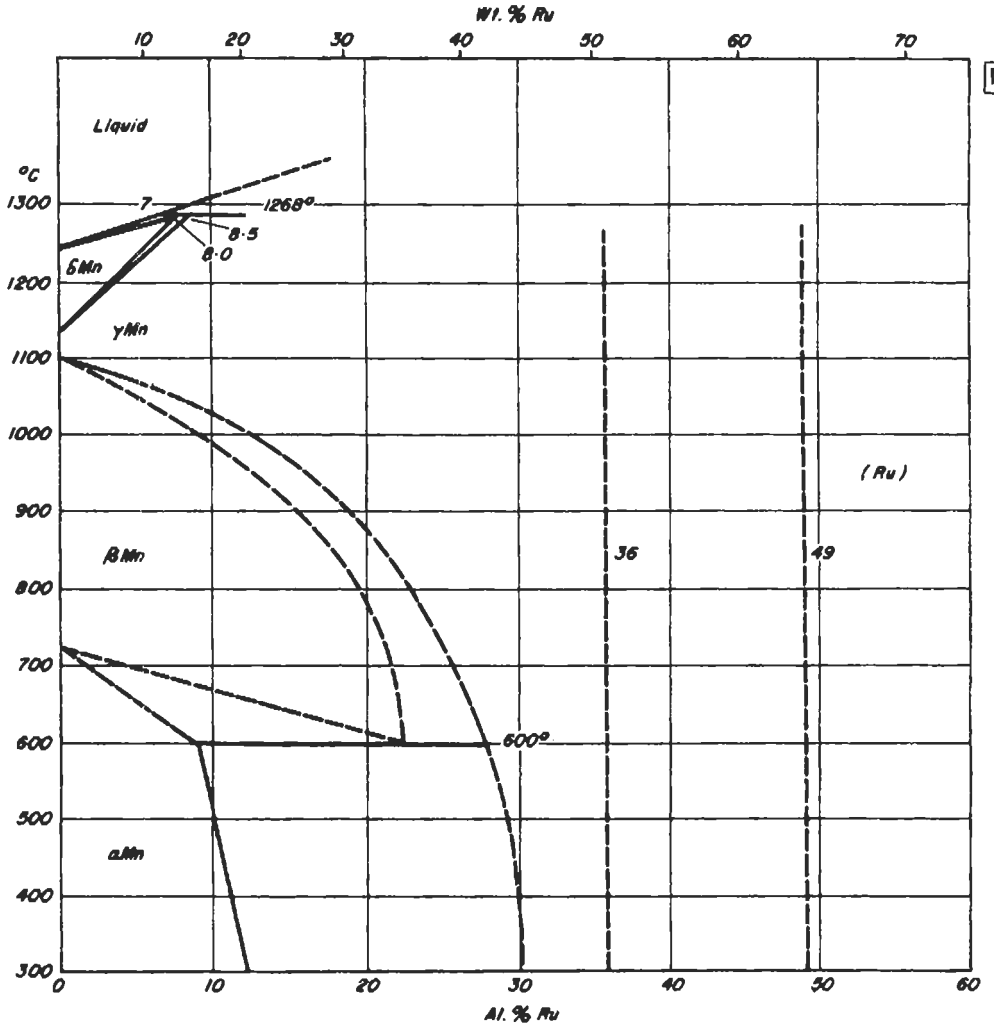


Mn–Pu

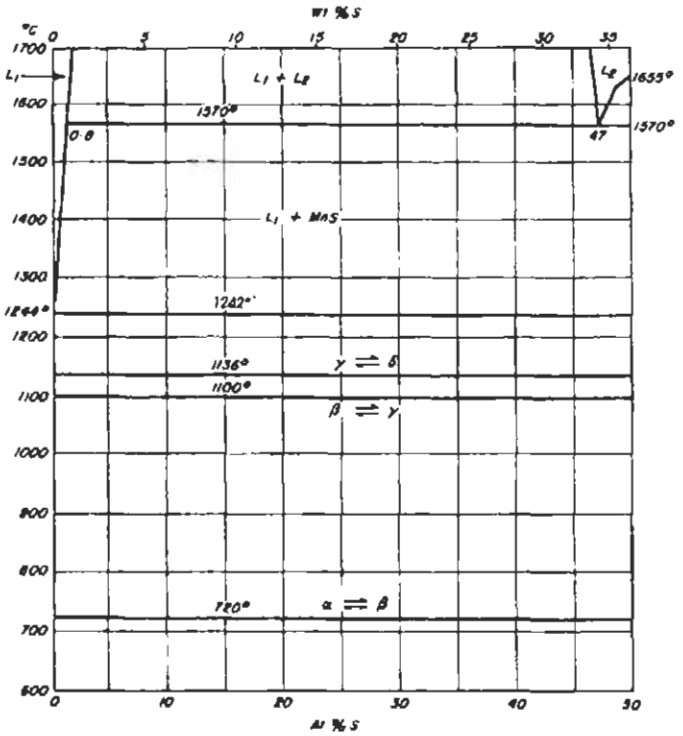


Mn–Rh

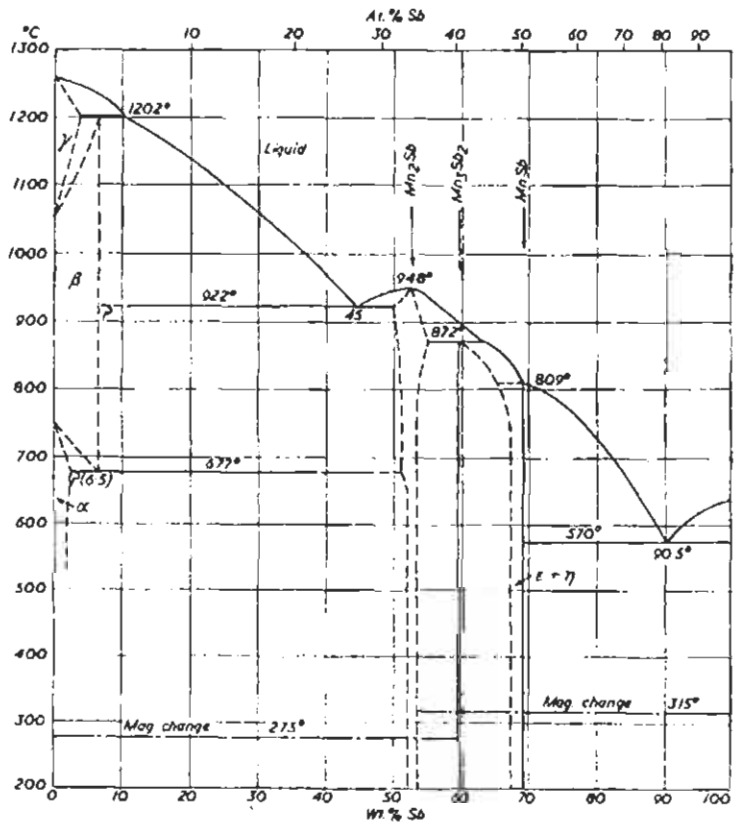


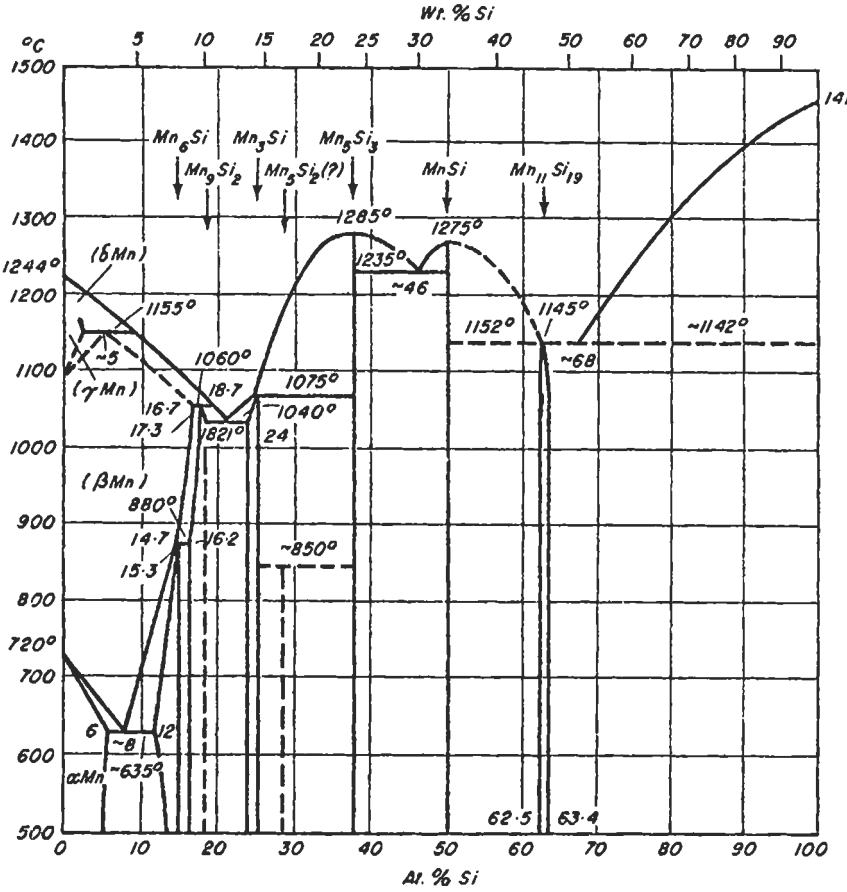

Wt. % Ru
10
20
30
40
50
60
70
Mn–Ru
Liquid
°C
1300
1200
1100
1000
900
800
700
600
500
400
300
7
1268°
8·5
8·0
δMn
γMn
βMn
αMn
(Ru)
36
49
600°
0
10
20
30
40
50
60
At. % Ru

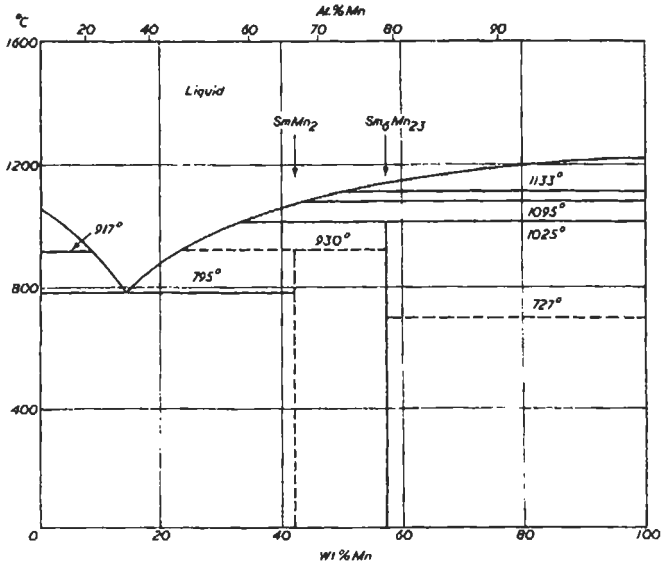
Mn–S


Wt % S
°C
L1
L1 + L2
L2
1655°
1570°
0·8
47
L1 + MnS
1244°
1242°
1136°
γ ⇌ δ
1100°
β ⇌ γ
780°
α ⇌ β
At % S

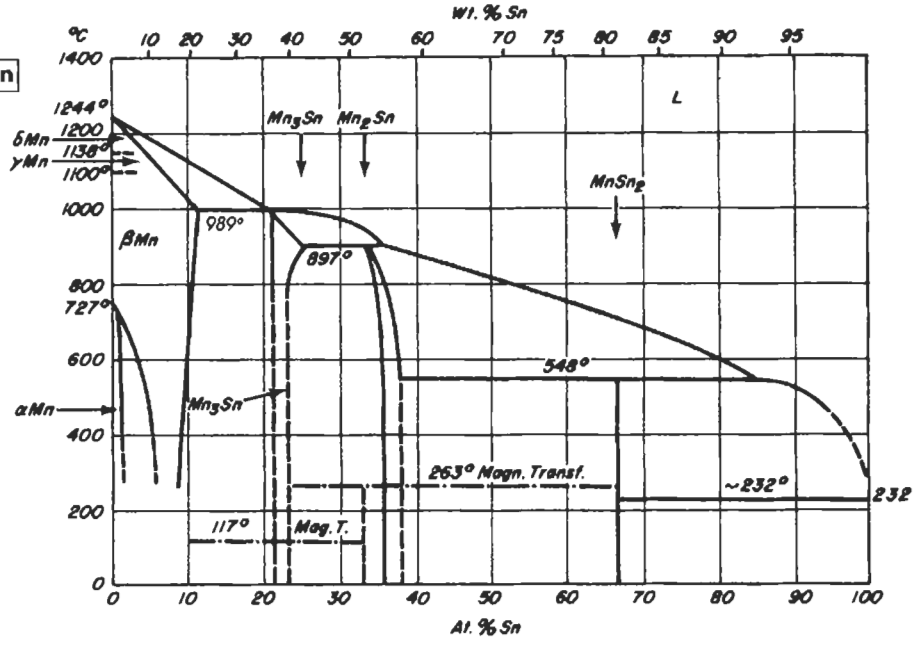
Mn–Sb


At.% Sb
°C
1202°
Liquid
Mn2Sb
Mn1Sb2
MnSb2
948°
922°
45
872°
809°
677°
α(6·5)
570°
90·5°
ε + η
Mag change
273°
Mag change
315°
Wt.% Sb

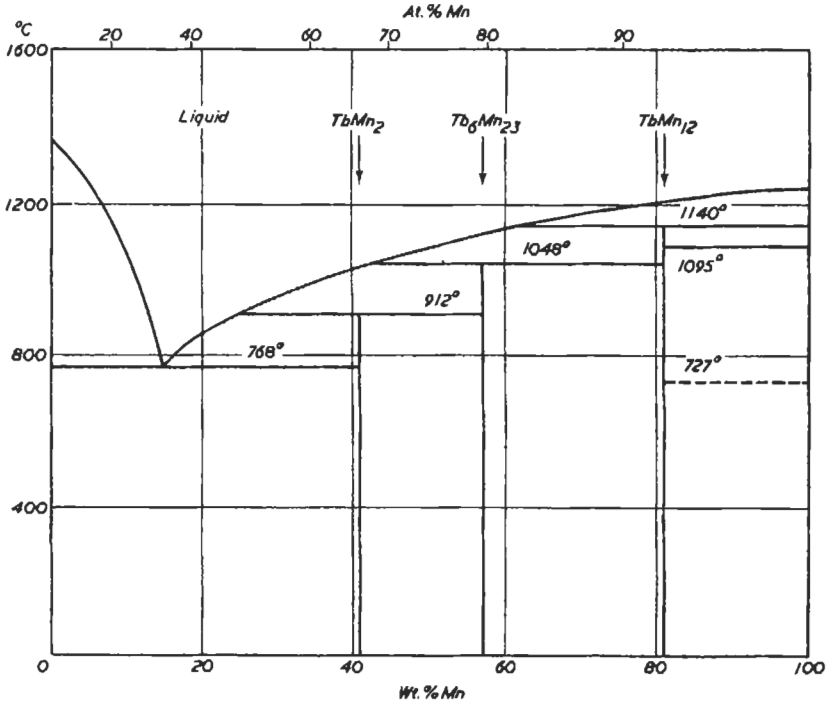

Wt. % Si
°C
Mn–Si
1412°
Mn_6Si
Mn_3Si
Mn_5Si_3
Mn_9Si_2
Mn_5Si_2(?)
MnSi
$Mn_{11}Si_{19}$
1285°
1275°
1235°
~46
1244°
(δMn)
1155°
1145°
1152°
~1142°
~68
~5
(γMn)
1060°
18·7
1075°
16·7
17·3
1040°
1821°
24
(βMn)
880°
14·7
16·2
15·3
~850°
720°
6
~8
12
αMn
~635°
62·5
63·4
At. % Si


At.% Mn
°C
Mn–Sm
Liquid
$SmMn_2$
Sm_6Mn_{23}
1133°
1095°
1025°
917°
930°
795°
727°
Wt % Mn

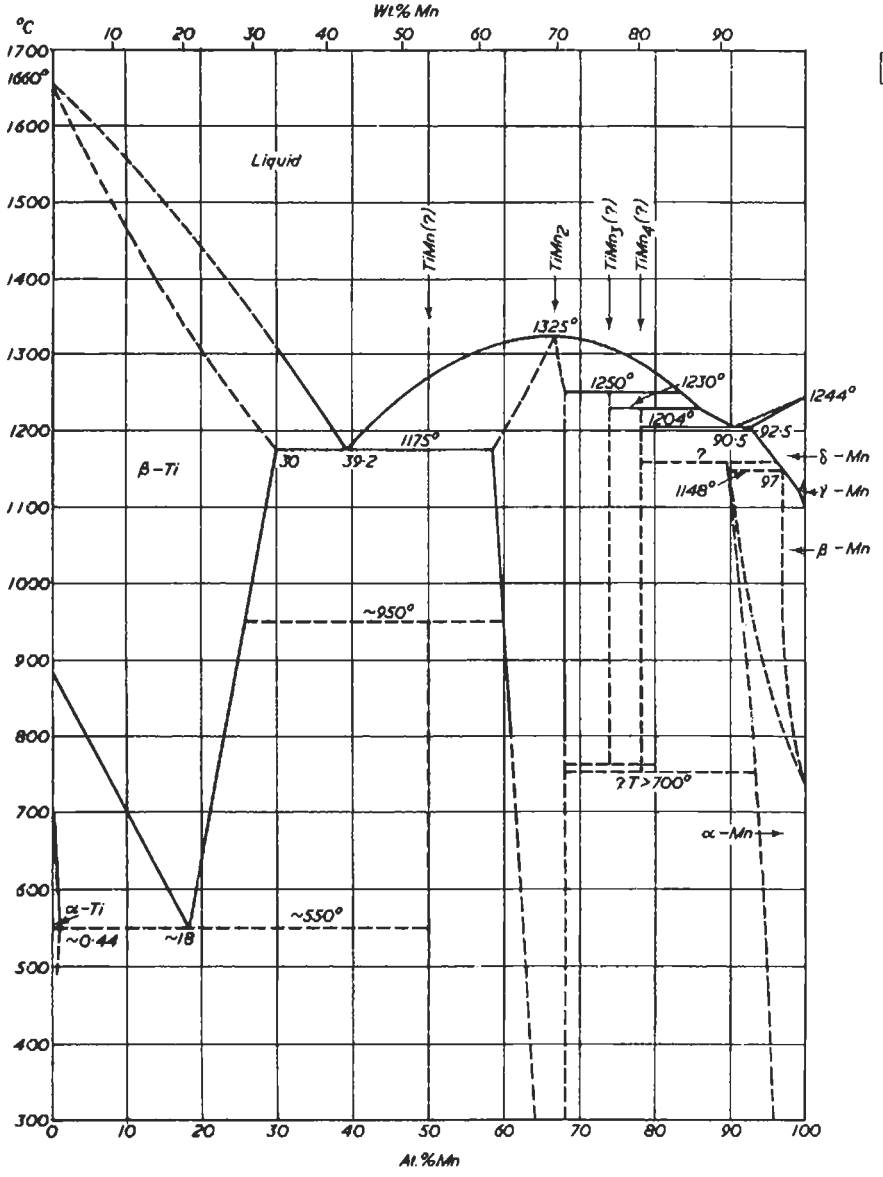
Mn–Sn


Wt. % Sn
°C
10 20 30 40 50 60 70 75 80 85 90 95
1400
1244°
δMn 1200
1138°
γMn
1100°
1000
800
727°
600
400
200
0
Mn3Sn
Mn2Sn
L
MnSn2
βMn
989°
897°
548°
αMn
Mn3Sn
263° Magn. Transf.
~232°
232
117°
Mag. T.
0 10 20 30 40 50 60 70 80 90 100
At. % Sn

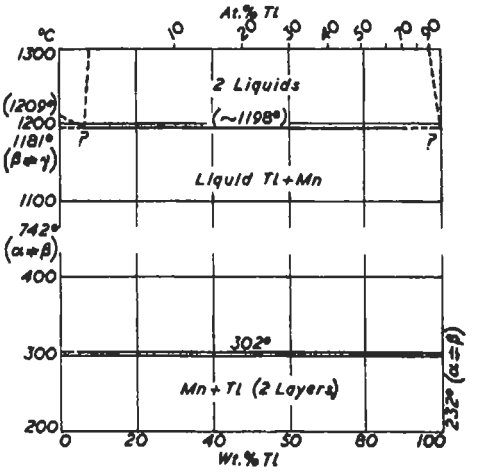
Mn–Tb


At. % Mn
°C
20 40 60 70 80 90
1600
Liquid
TbMn2
Tb6Mn23
TbMn12
1200
1140°
1048°
1095°
912°
800
768°
727°
400
0 20 40 60 80 100
Wt. % Mn

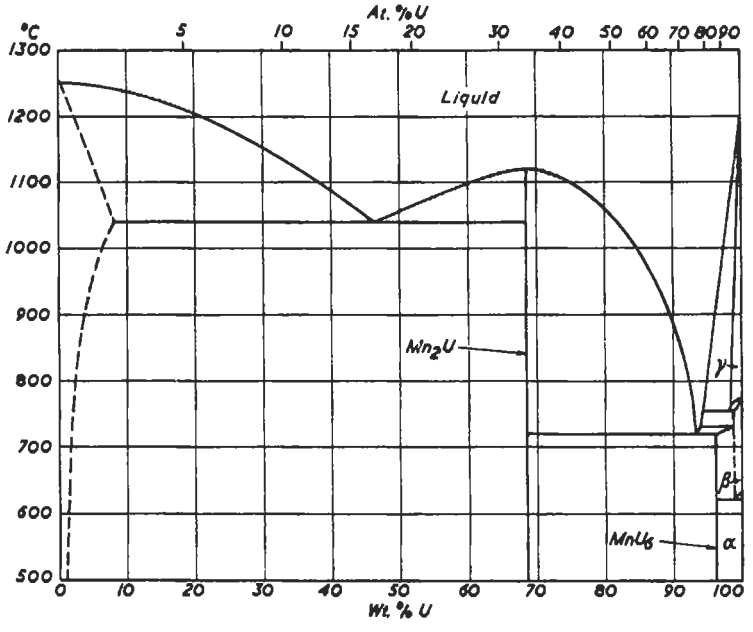
Mn–Ti


°C
Wt% Mn
10
20
30
40
50
60
70
80
90
1700
1660°
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
Liquid
β–Ti
TiMn(?)
TiMn2
TiMn3(?)
TiMn4(?)
1325°
1250°
1230°
1244°
1204°
1175°
30
39·2
90·5
92·5
?
1148°
97
δ–Mn
γ–Mn
β–Mn
~950°
?T>700°
α–Mn
α–Ti
~0·44
~18
~550°
0
10
20
30
40
50
60
70
80
90
100
At.%Mn

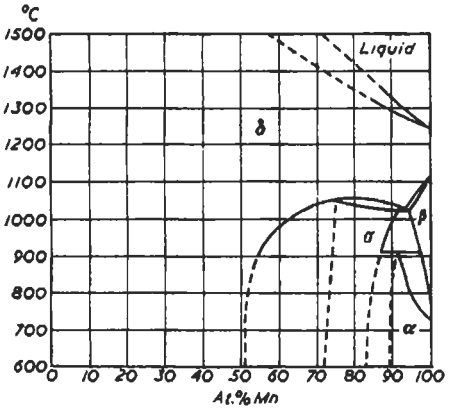
Mn–Tl

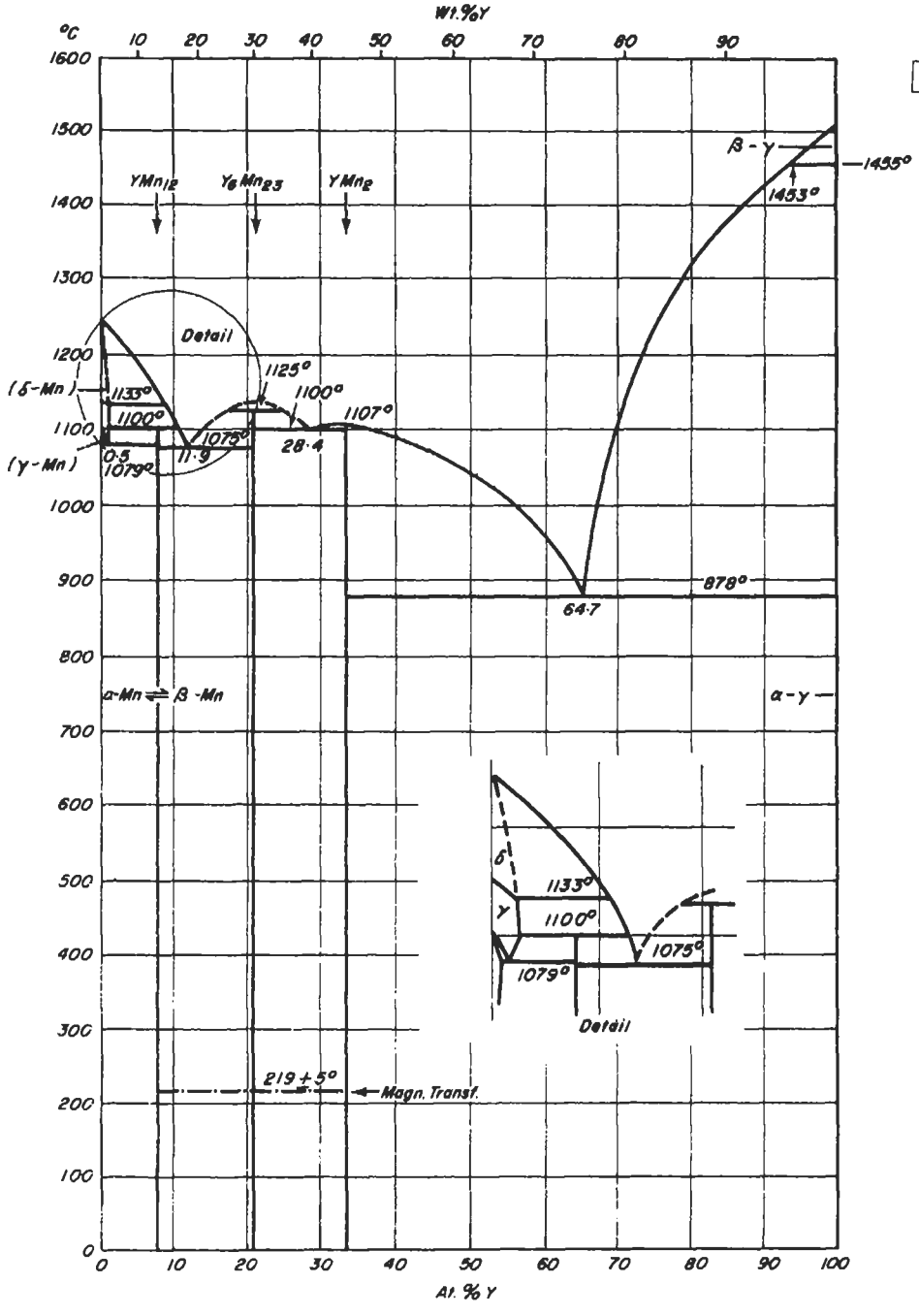

°C
At.% Tl
10
20
30
40
50
70
90
1300
(1209°)
1200
1181°
(β⇌γ)
1100
742°
(α⇌β)
400
300
200
2 Liquids
(~1198°)
?
?
Liquid Tl + Mn
302°
Mn + Tl (2 Layers)
232° (α⇌β)
0
20
40
50
80
100
Wt.% Tl

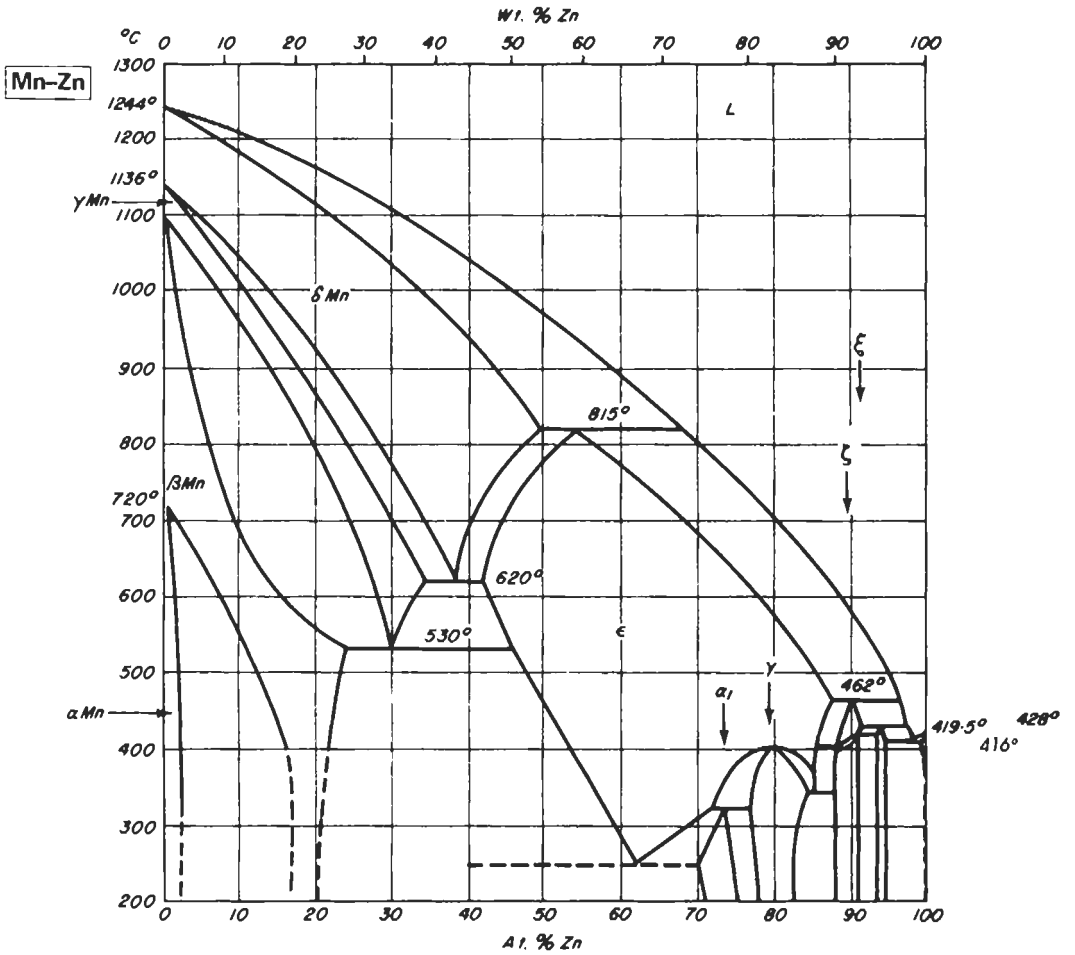
Mn–U


°C
At.% U
5
10
15
20
30
40
50
60
70
80
90
1300
1200
1100
1000
900
800
700
600
500
Liquid
Mn2U
γ
β
MnU6
α
0
10
20
30
40
50
60
70
80
90
100
Wt. % U

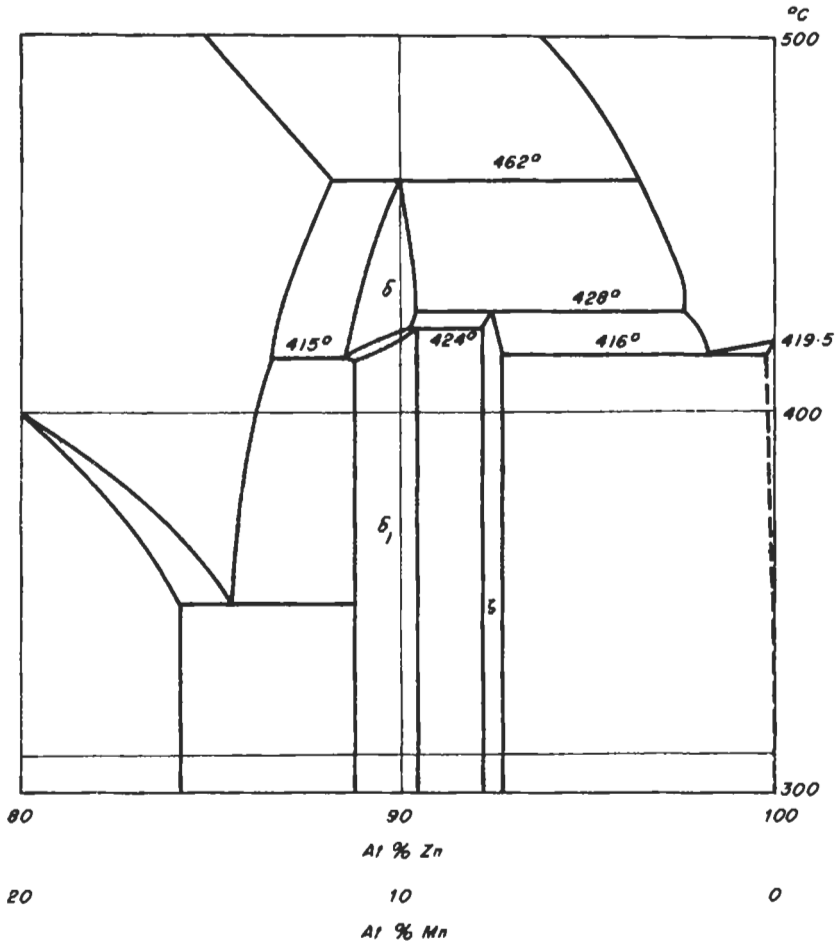
Mn–V


°C
1500
1400
1300
1200
1100
1000
900
800
700
600
Liquid
δ
β
α
α
0
10
20
30
40
50
60
70
80
90
100
At.% Mn


Mn–Y
Wt.%Y
°C
At. % Y
YMn12
Y6Mn23
YMn2
β - γ
1455°
1453°
Detail
1125°
1100°
1107°
1133°
1100°
1075°
11·9
28·4
0·5
1079°
(δ-Mn)
(γ-Mn)
878°
64·7
α-Mn ⇌ β-Mn
α - γ
δ
γ
1133°
1100°
1075°
1079°
Detail
219 ± 5°
Magn. Transf.

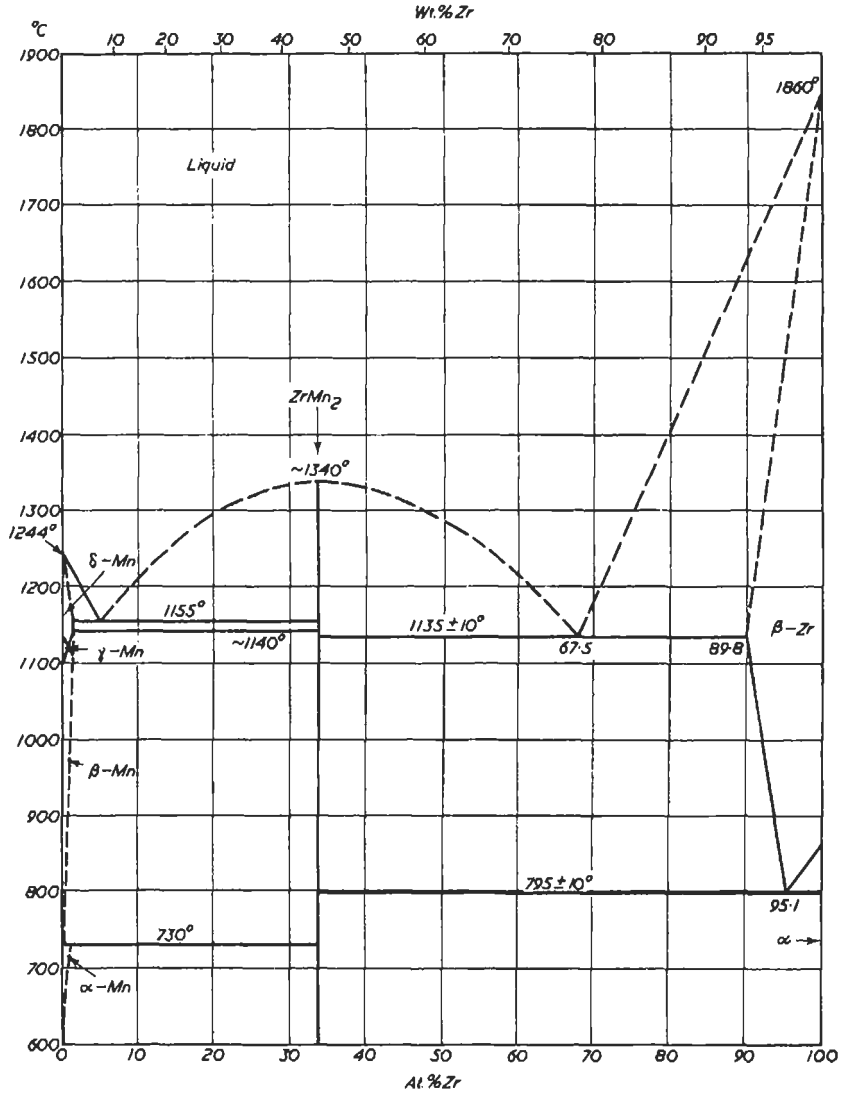


see also detail p. 11–371

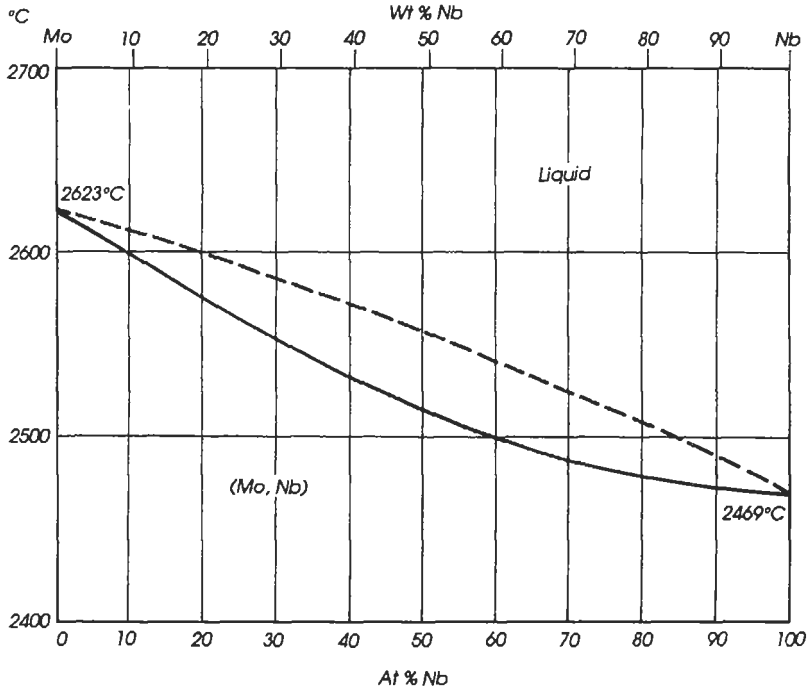

°C
500
462°
δ
428°
415°
424°
416°
419·5
400
δ1
ζ
300
80
90
100
At % Zn
20
10
0
At % Mn

Mn–Zn
detail

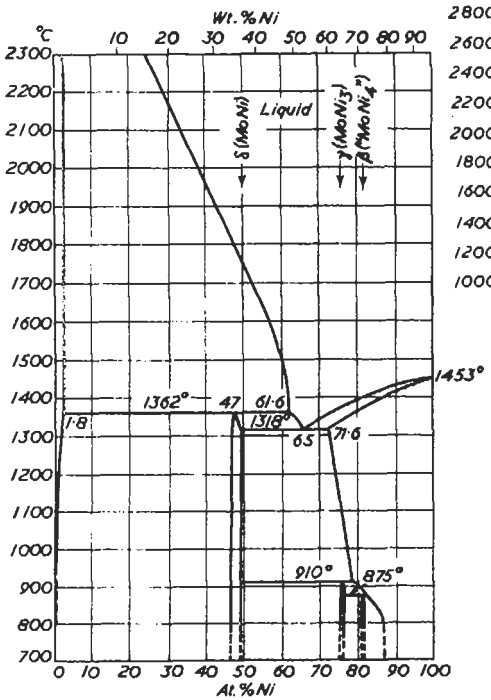
Mn–Zr


Wt.% Zr
°C
10 20 30 40 50 60 70 80 90 95
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
Liquid
ZrMn2
~1340°
1860°
1244°
δ–Mn
1155°
~1140°
1135 ± 10°
67·5
89·8
β–Zr
γ–Mn
β–Mn
795 ± 10°
95·1
α
730°
α–Mn
0 10 20 30 40 50 60 70 80 90 100
At.% Zr

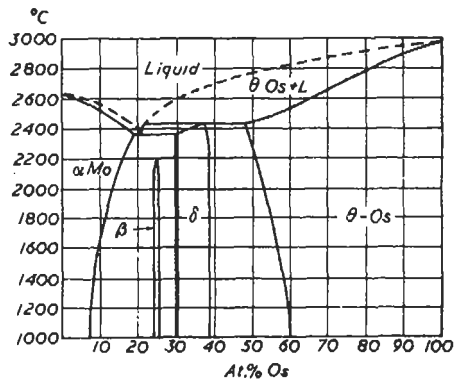
Mo–Nb



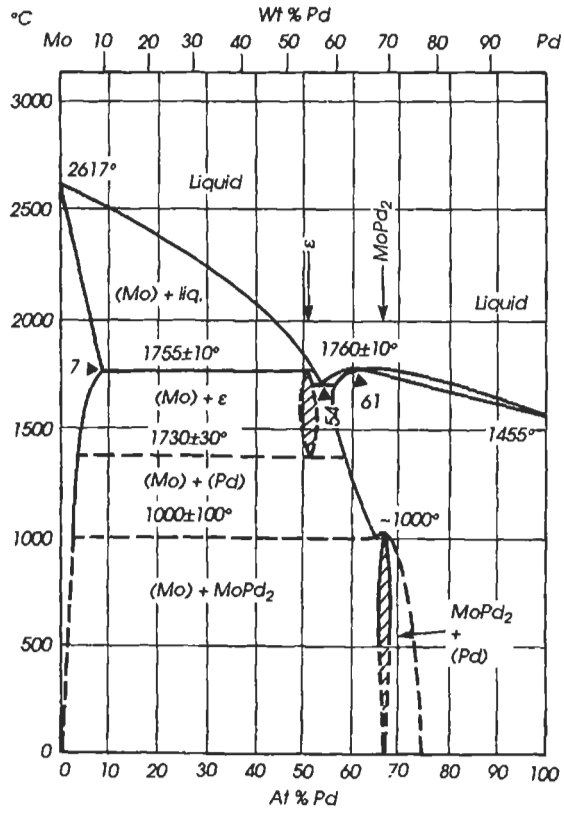
Mo–Ni



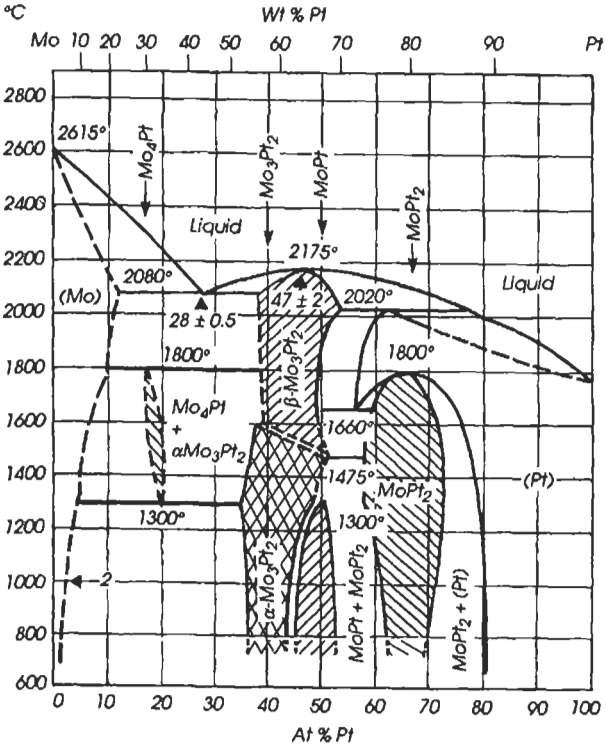
Mo–Os



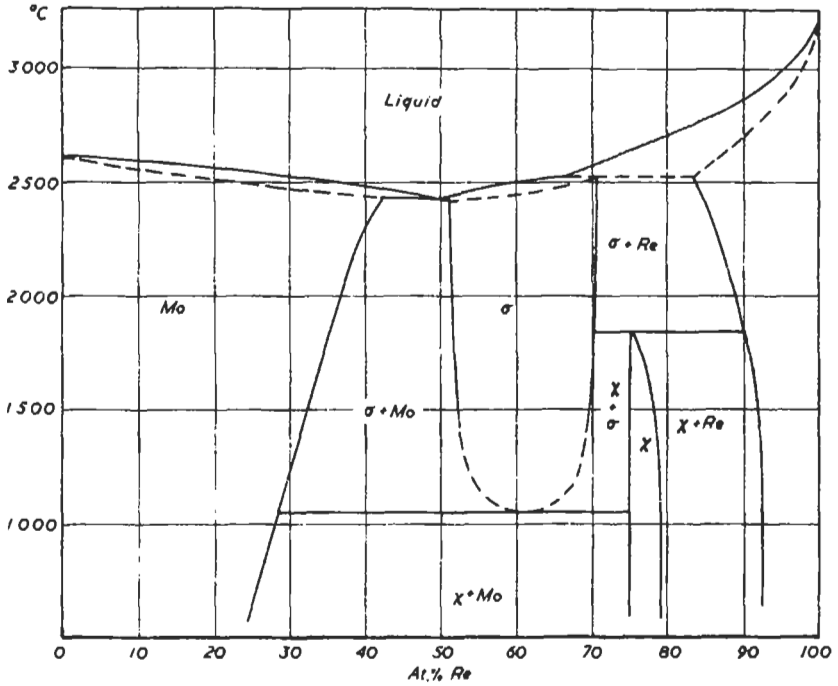
Mo–Pd


°C
Wt % Pd
Mo 10 20 30 40 50 60 70 80 90 Pd
3000
2500
2000
1500
1000
500
0
2617°
Liquid
ε
MoPd2
(Mo) + liq.
Liquid
7
1755±10°
1760±10°
(Mo) + ε
54
61
1730±30°
1455°
(Mo) + (Pd)
1000±100°
~1000°
(Mo) + MoPd2
MoPd2
+
(Pd)
0 10 20 30 40 50 60 70 80 90 100
At % Pd

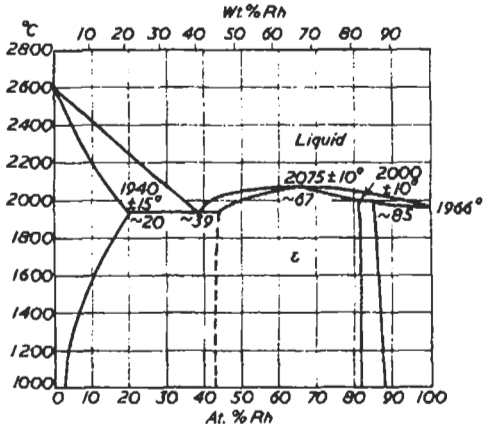
Mo–Pt


°C
Wt % Pt
Mo 10 20 30 40 50 60 70 80 90 Pt
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
2615°
Mo4Pt
Mo3Pt2
MoPt
MoPt2
Liquid
2175°
(Mo)
2080°
47 ± 2
2020°
Liquid
28 ± 0.5
1800°
1800°
β-Mo3Pt2
Mo4Pt
+
αMo3Pt2
1660°
1475°
MoPt2
(Pt)
1300°
1300°
α-Mo3Pt2
MoPt + MoPt2
MoPt2 + (Pt)
2
0 10 20 30 40 50 60 70 80 90 100
At % Pt

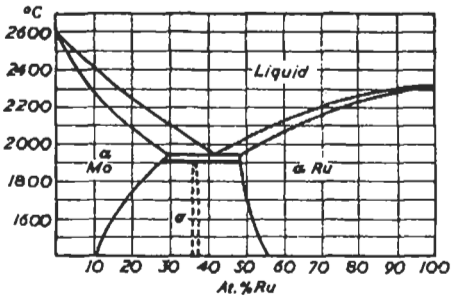
Mo–Re



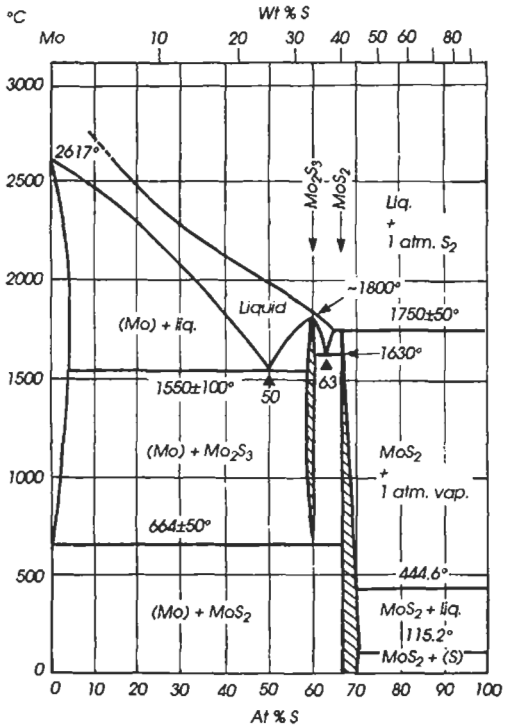
Mo–Rh



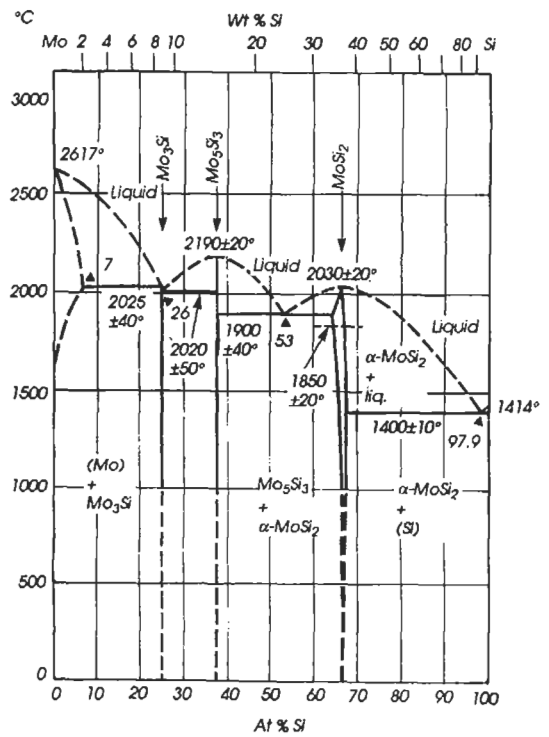
Mo–Ru

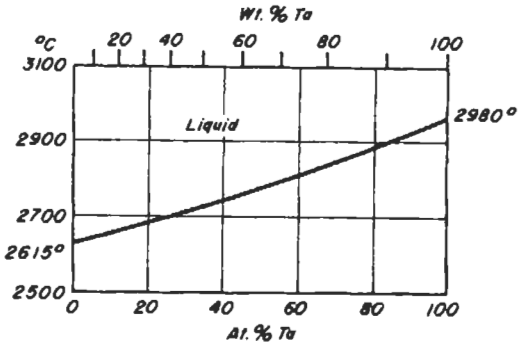


Mo–S

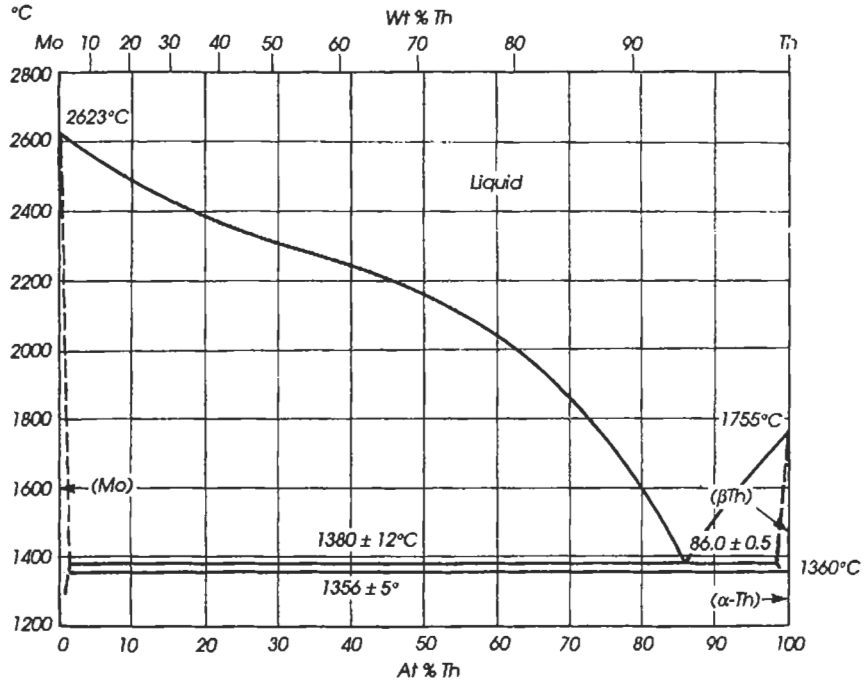

°C
Wt % S
Mo 10 20 30 40 50 60 80
3000
2500
2000
1500
1000
500
0
2617°
Mo_2S_3
MoS_2
Liq. + 1 atm. S_2
~1800°
1750±50°
Liquid
(Mo) + liq.
1630°
1550±100°
50
63
(Mo) + Mo_2S_3
MoS_2 + 1 atm. vap.
664±50°
444.6°
(Mo) + MoS_2
MoS_2 + liq.
115.2°
MoS_2 + (S)
0 10 20 30 40 50 60 70 80 90 100
At % S

Mo–Si


°C
Wt % Si
Mo 2 4 6 8 10 20 30 40 50 60 80 Si
3000
2500
2000
1500
1000
500
0
2617°
Liquid
Mo_3Si
Mo_5Si_3
$MoSi_2$
2190±20°
Liquid
2030±20°
7
2025 ±40°
26
2020 ±50°
1900 ±40°
53
1850 ±20°
Liquid
α-$MoSi_2$ + liq.
1414°
1400±10°
97.9
(Mo) + Mo_3Si
Mo_5Si_3 + α-$MoSi_2$
α-$MoSi_2$ + (Si)
0 10 20 30 40 50 60 70 80 90 100
At % Si

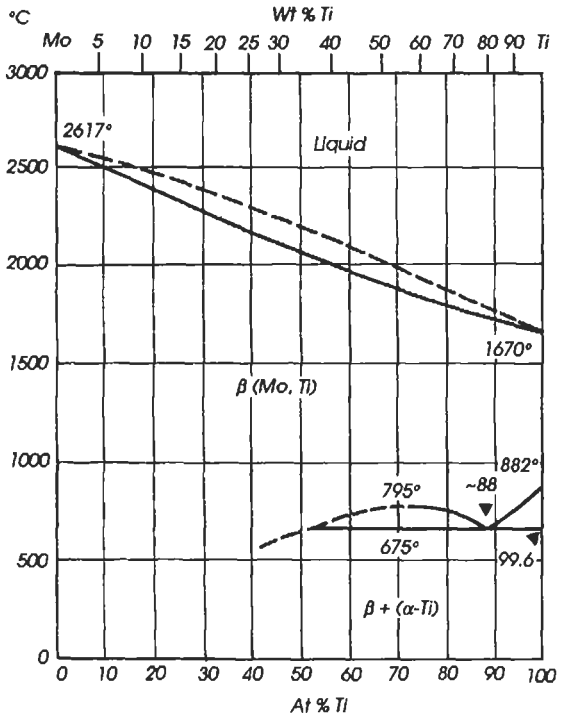

Wt. % Ta
°C
20
40
60
80
100
3100
2900
2700
2615°
2500
Liquid
2980°
0
20
40
60
80
100
At. % Ta

Mo–Ta

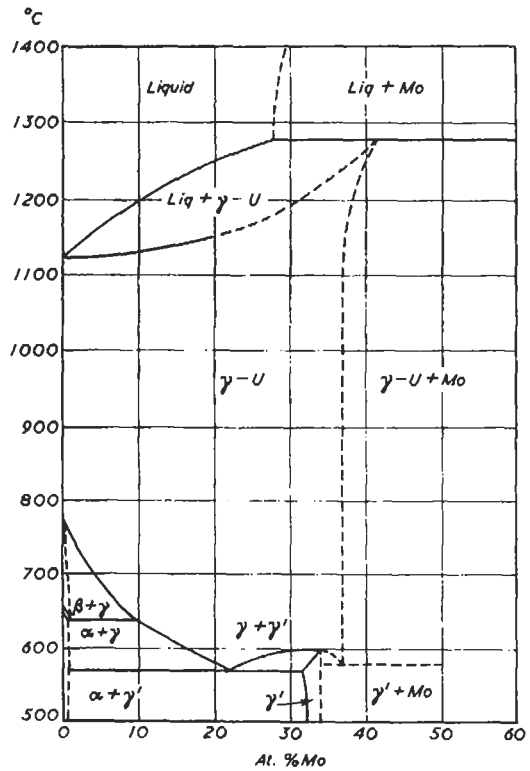

°C
Wt % Th
Mo
10
20
30
40
50
60
70
80
90
Th
2800
2600
2400
2200
2000
1800
1600
1400
1200
2623°C
Liquid
1755°C
(Mo)
(βTh)
1380 ± 12°C
86.0 ± 0.5
1360°C
1356 ± 5°
(α-Th)
0
10
20
30
40
50
60
70
80
90
100
At % Th

Mo–Th

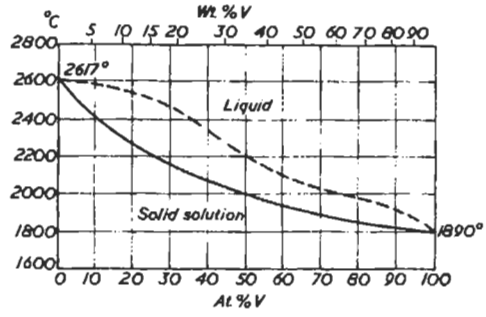
Mo–Ti


°C
Wt % Ti
Mo 5 10 15 20 25 30 40 50 60 70 80 90 Ti
3000
2500
2000
1500
1000
500
0
2617°
Liquid
1670°
β (Mo, Ti)
882°
795°
~88
675°
99.6
β + (α-Ti)
0 10 20 30 40 50 60 70 80 90 100
At % Ti

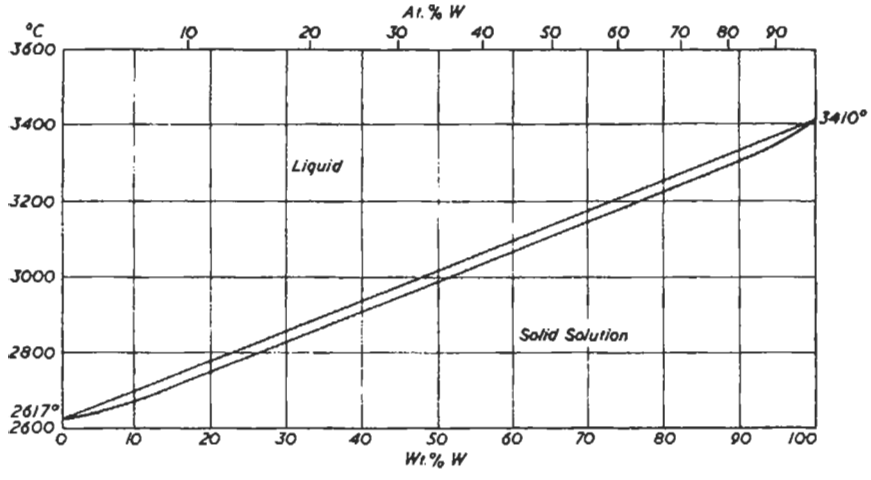
Mo–U


°C
1400
1300
1200
1100
1000
900
800
700
600
500
Liquid
Liq + Mo
Liq + γ - U
γ - U
γ - U + Mo
β + γ
α + γ
γ + γ'
α + γ'
γ'
γ' + Mo
0 10 20 30 40 50 60
At. % Mo

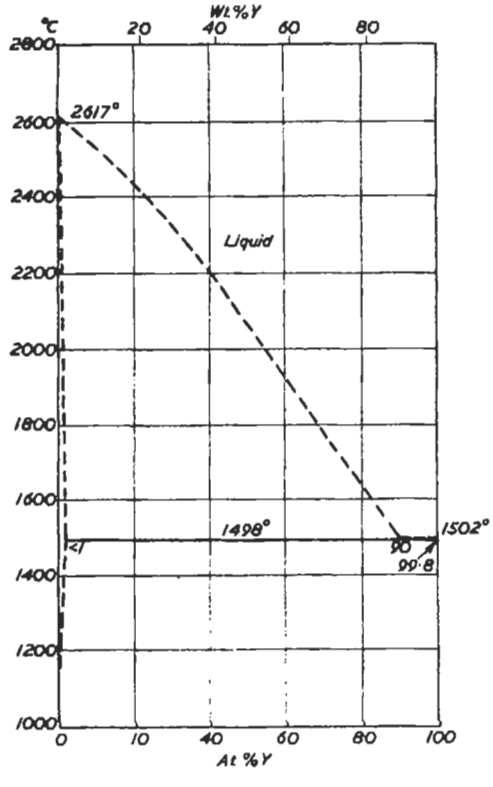
Mo–V


°C
Wt.% V
5 10 15 20 30 40 50 60 70 80 90
2800
2600
2400
2200
2000
1800
1600
2617°
Liquid
Solid solution
1890°
0 10 20 30 40 50 60 70 80 90 100
At.% V

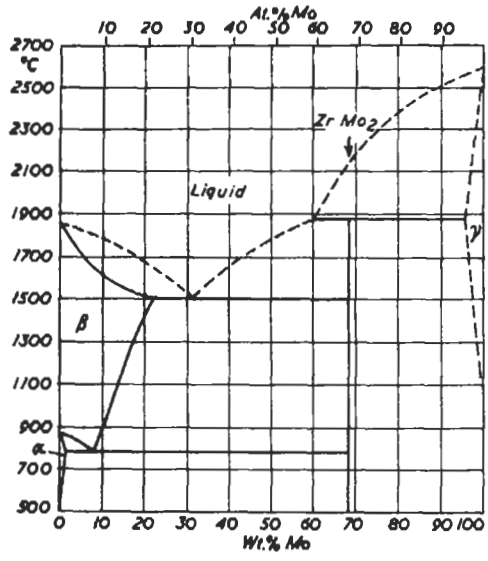
Mo–W


°C
At.% W
10 20 30 40 50 60 70 80 90
3600
3400
3200
3000
2800
2617°
2600
Liquid
Solid Solution
3410°
0 10 20 30 40 50 60 70 80 90 100
Wt.% W

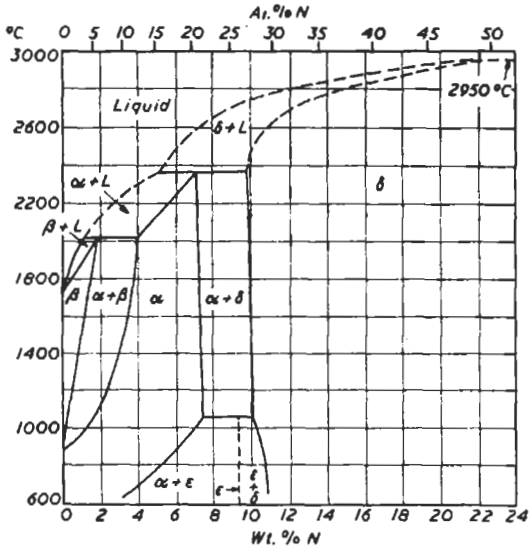
Mo–Y


°C
Wt.% Y
20 40 60 80
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
2617°
Liquid
1498°
1502°
<1
90
99·8
0 10 40 60 80 100
At.% Y

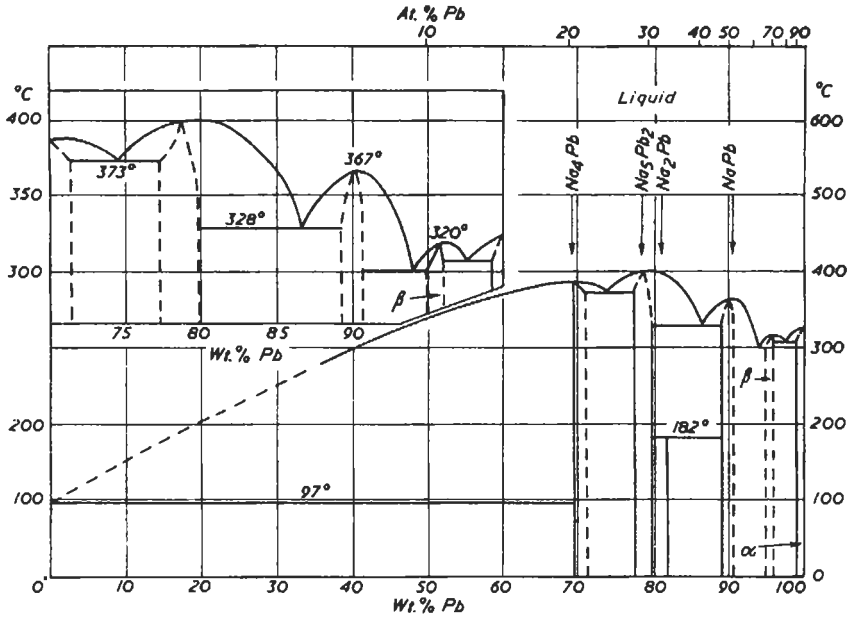
Mo–Zr


At.% Mo
10 20 30 40 50 60 70 80 90
2700 °C
2500
2300
2100
1900
1700
1500
1300
1100
900
700
500
Zr Mo2
Liquid
β
α
γ
0 10 20 30 40 50 60 70 80 90 100
Wt.% Mo

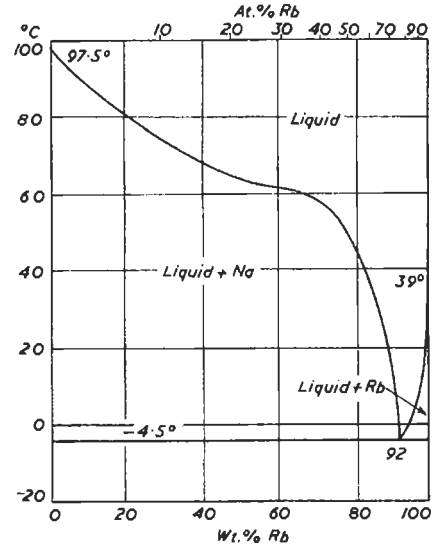
N–Ti


At.% N
°C 0 5 10 15 20 25 30 35 40 45 50
3000
2600
2200
1800
1400
1000
600
Liquid
δ+L
2950 °C
α+L
β+L
δ
β
α+β
α
α+δ
α+ε
ε→ε+δ
0 2 4 6 8 10 12 14 16 18 20 22 24
Wt. % N

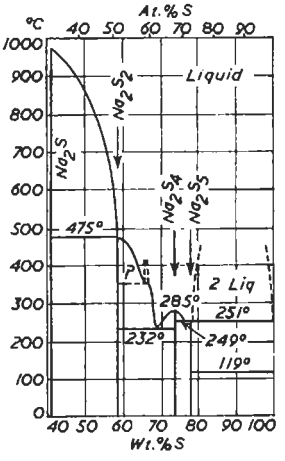
Na–Pb



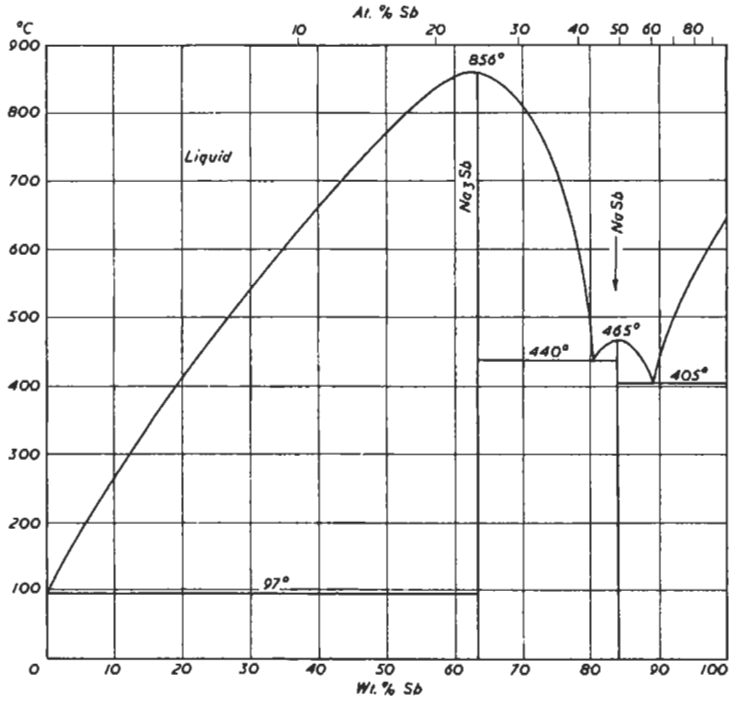
Na–Rb



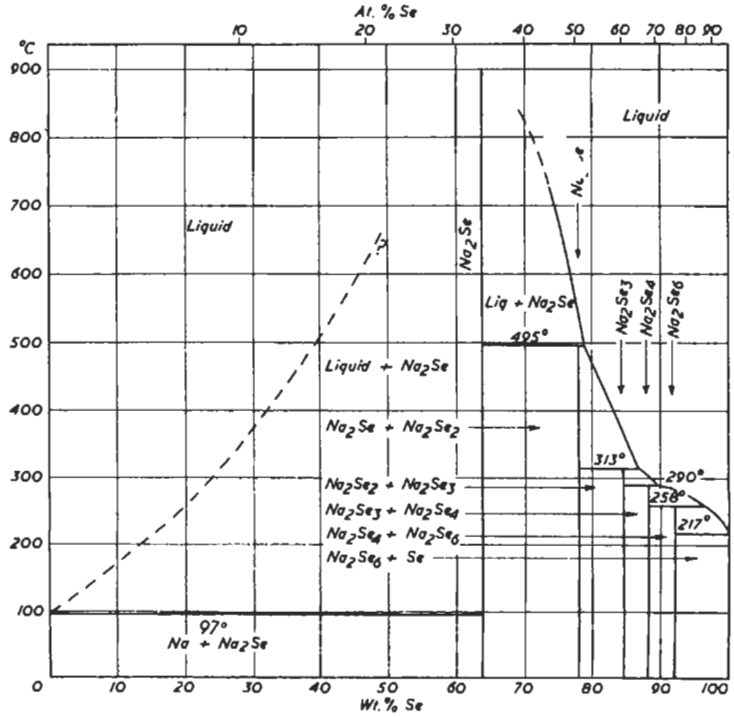
Na–S



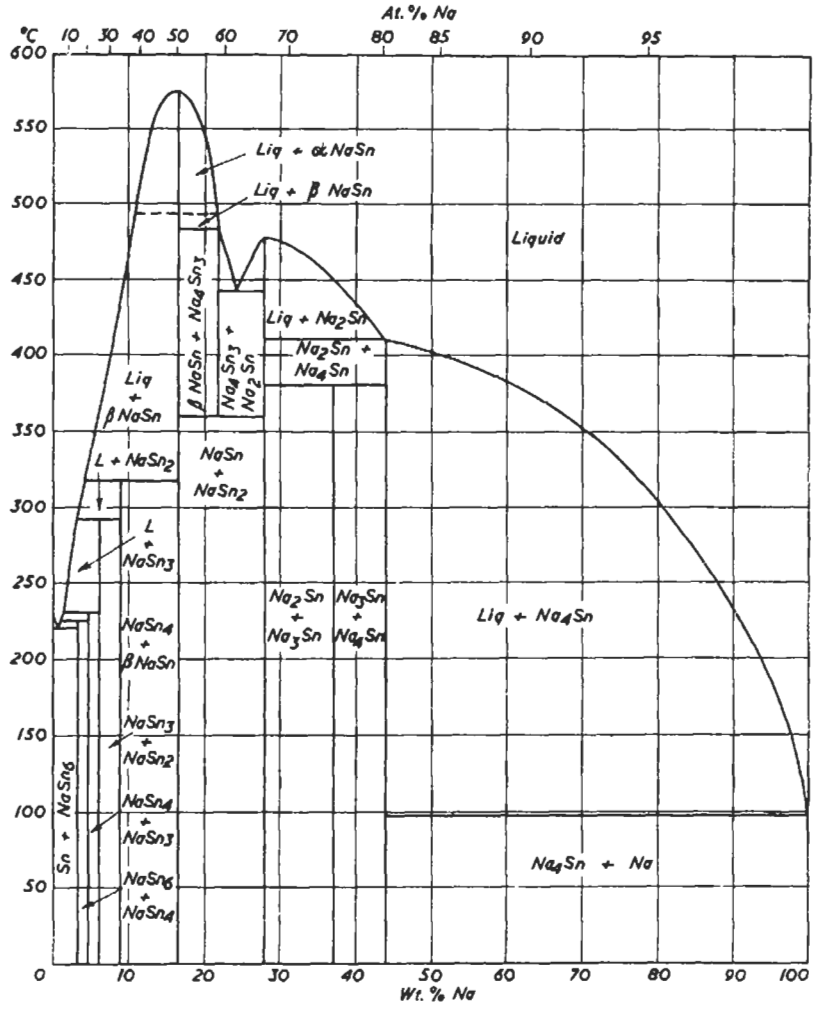
Na–Sb


At. % Sb
°C
Liquid
856°
Na3Sb
NaSb
465°
440°
405°
97°
Wt. % Sb

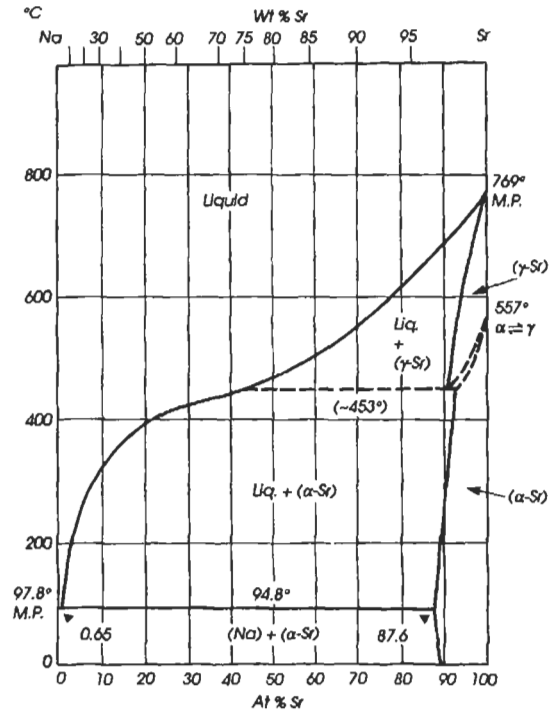
Na–Se


At. % Se
°C
Liquid
Na2Se
Liq + Na2Se
Na2Se3
Na2Se4
Na2Se6
495°
Liquid + Na2Se
Na2Se + Na2Se2
313°
290°
Na2Se2 + Na2Se3
258°
Na2Se3 + Na2Se4
Na2Se4 + Na2Se6
217°
Na2Se6 + Se
97°
Na + Na2Se
Wt. % Se

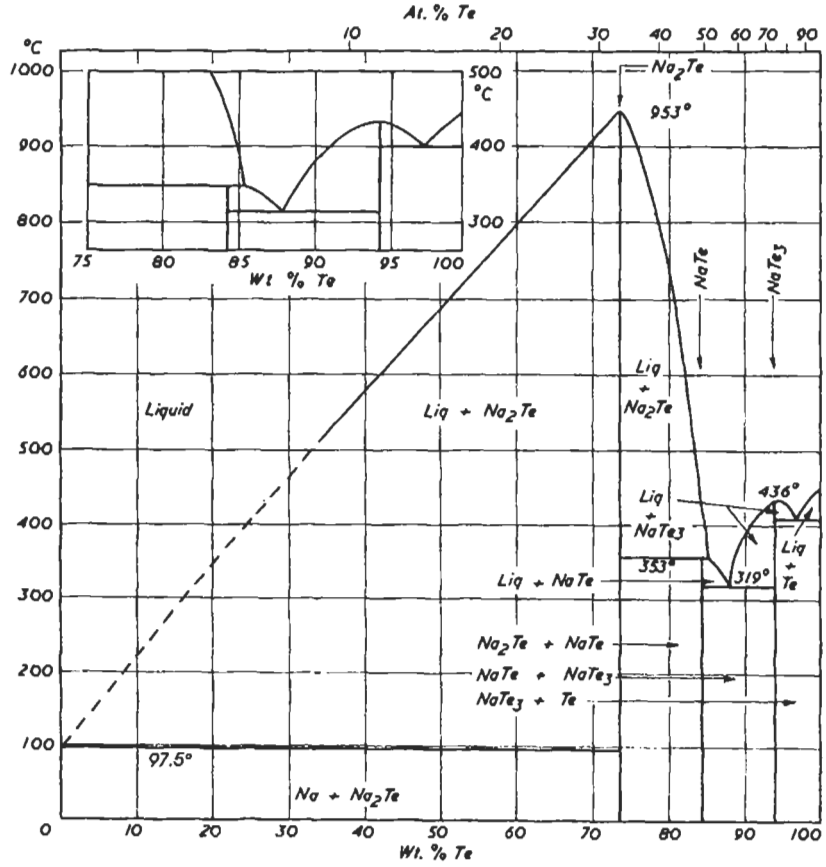
Na–Sn


At.% Na
°C
10
30
40
50
60
70
80
85
90
95
600
550
500
450
400
350
300
250
200
150
100
50
0
Liq + α NaSn
Liq + β NaSn
Liquid
Liq + Na2Sn
Na2Sn + Na4Sn
β NaSn + Na4Sn3
Na4Sn3 + Na2Sn
Liq + β NaSn
L + NaSn2
NaSn + NaSn2
L + NaSn3
Na2Sn + Na3Sn
Na3Sn + Na4Sn
Liq + Na4Sn
NaSn4 + β NaSn
NaSn3 + NaSn2
NaSn4 + NaSn3
Sn + NaSn6
NaSn6 + NaSn4
Na4Sn + Na
10
20
30
40
50
60
70
80
90
100
Wt. % Na

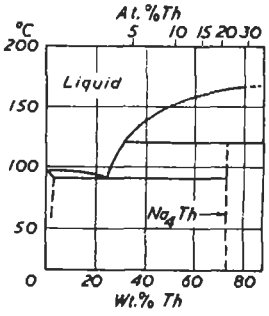
Na–Sr


°C
Wt % Sr
Na
30
50
60
70
75
80
85
90
95
Sr
800
600
400
200
0
Liquid
769°
M.P.
(γ-Sr)
557°
α ⇌ γ
Liq.
+
(γ-Sr)
(~453°)
Liq. + (α-Sr)
(α-Sr)
97.8°
M.P.
94.8°
0.65
(Na) + (α-Sr)
87.6
0
10
20
30
40
50
60
70
80
90
100
At % Sr

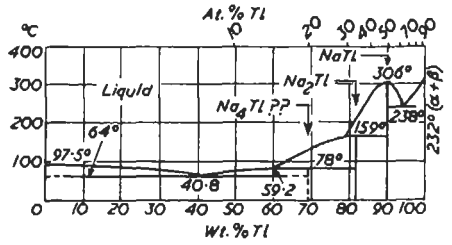
Na–Te


At. % Te
10
20
30
40
50
60
70
90
°C
1000
900
800
700
600
500
400
300
200
100
0
500
°C
400
300
75
80
85
90
95
100
Wt % Te
Na₂Te
953°
NaTe
NaTe₃
Liquid
Liq + Na₂Te
Liq
+
Na₂Te
Liq
+
NaTe₃
436°
353°
319°
Liq
+
Te
Liq + NaTe
Na₂Te + NaTe
NaTe + NaTe₃
NaTe₃ + Te
97.5°
Na + Na₂Te
10
20
30
40
50
60
70
80
90
100
Wt. % Te

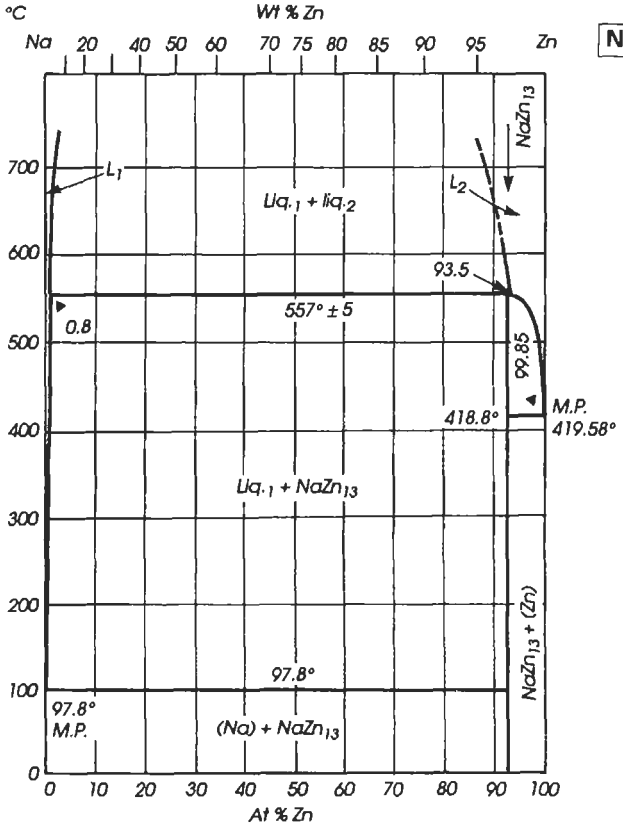
Na–Th



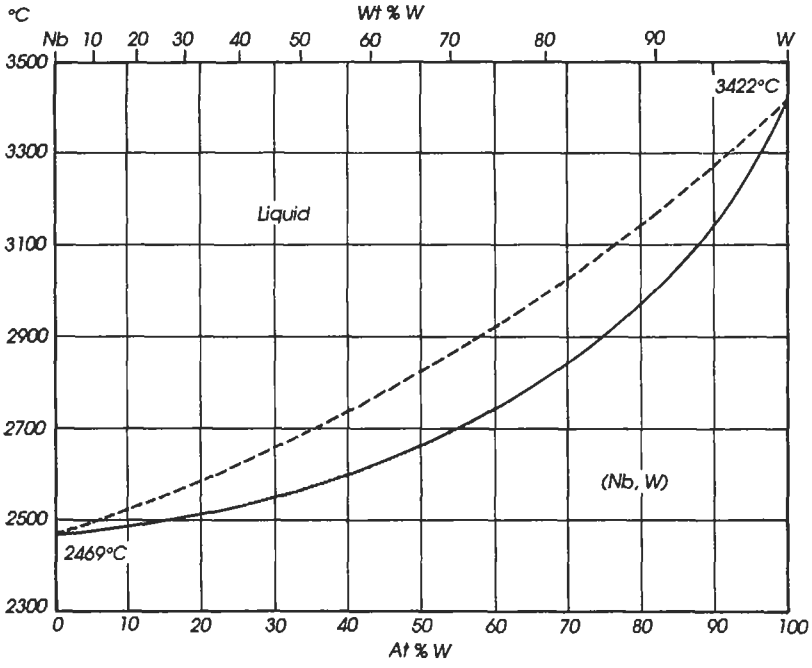
Na–Tl



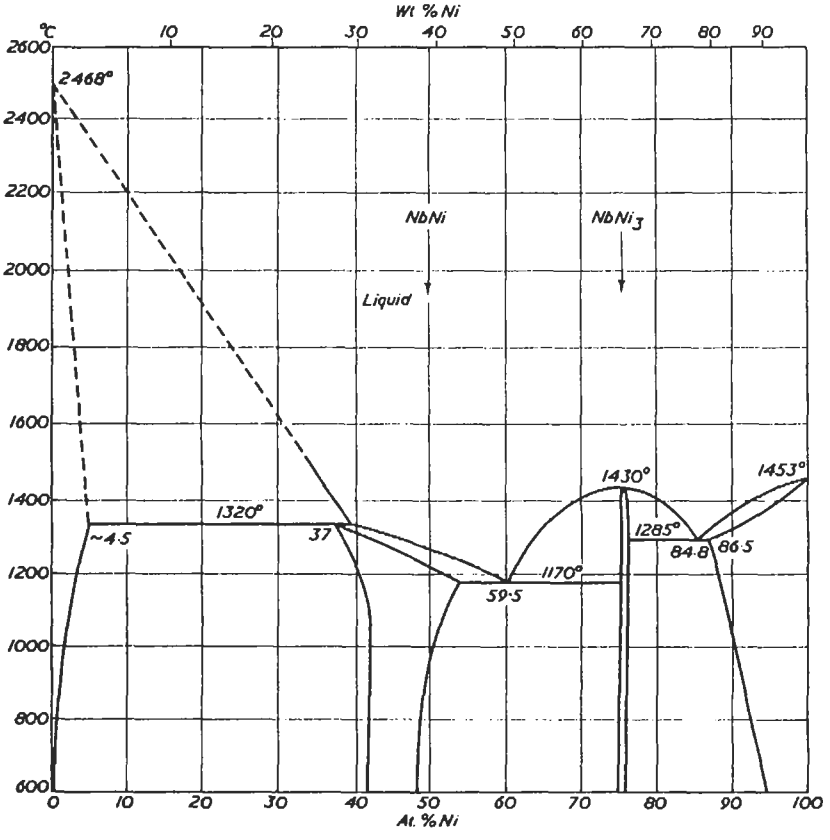
Na–Zn



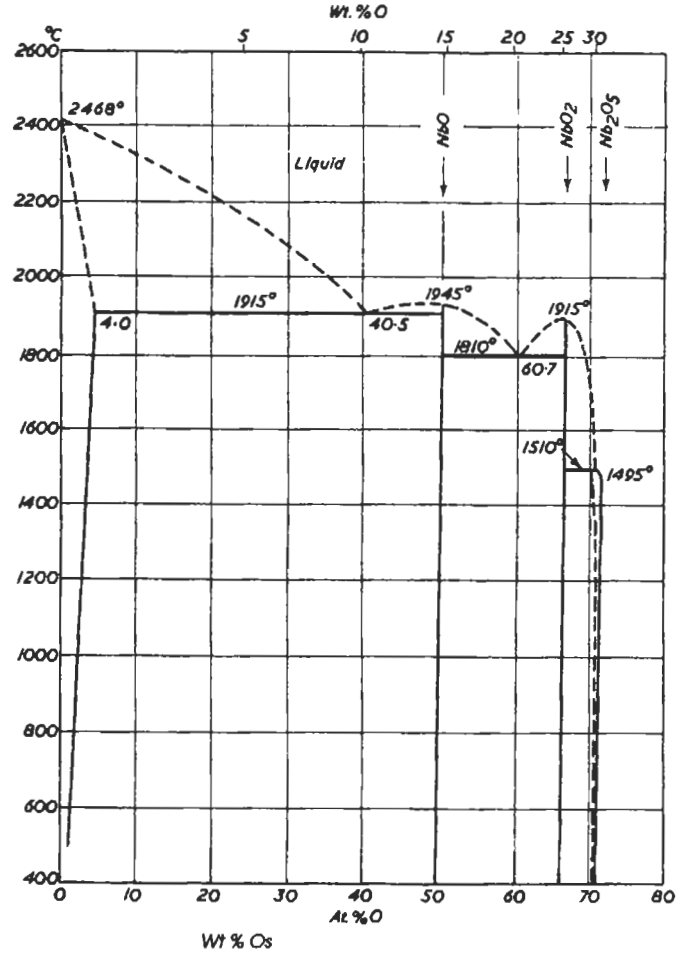
Nb–W


°C
Wt % W
Nb 10 20 30 40 50 60 70 80 90 W
3500
3300
3100
2900
2700
2500
2300
3422°C
Liquid
(Nb, W)
2469°C
0 10 20 30 40 50 60 70 80 90 100
At % W

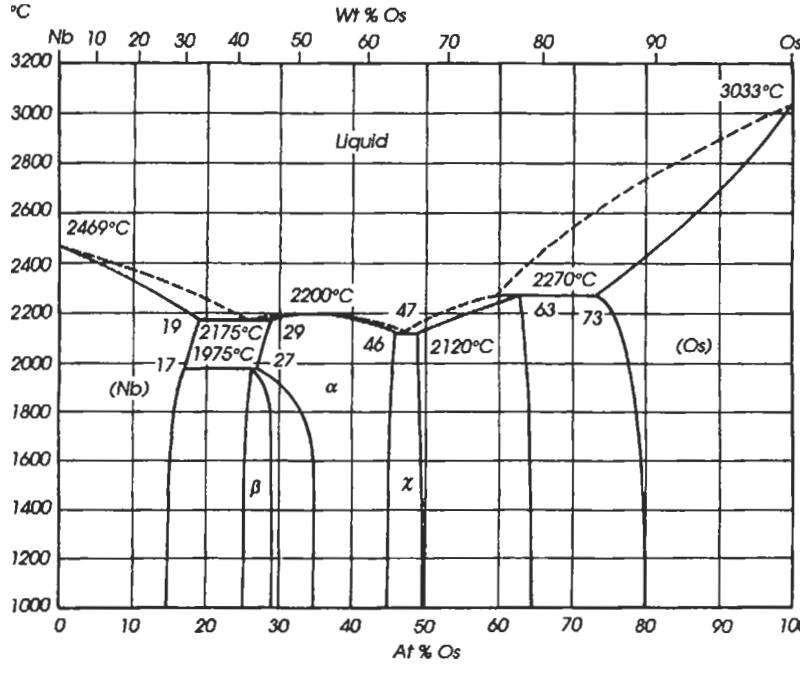
Nb–Ni


°C
Wt % Ni
10 20 30 40 50 60 70 80 90
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
2468°
NbNi
NbNi3
Liquid
1430°
1453°
1320°
1285°
~4·5
37
84·8
86·5
1170°
59·5
0 10 20 30 40 50 60 70 80 90 100
At. % Ni

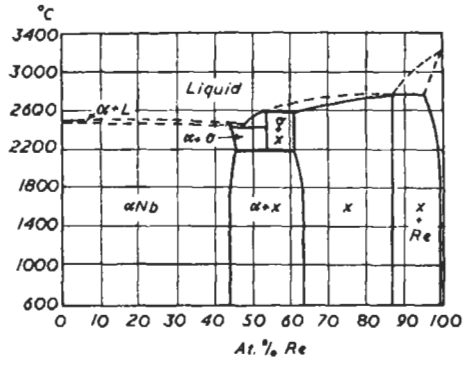
Nb–O


Wt. % O
°C
5
10
15
20
25
30
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
2468°
Liquid
NbO
NbO2
Nb2O5
1915°
1945°
1915°
4·0
40·5
1810°
60·7
1510°
1495°
0
10
20
30
40
50
60
70
80
At. % O

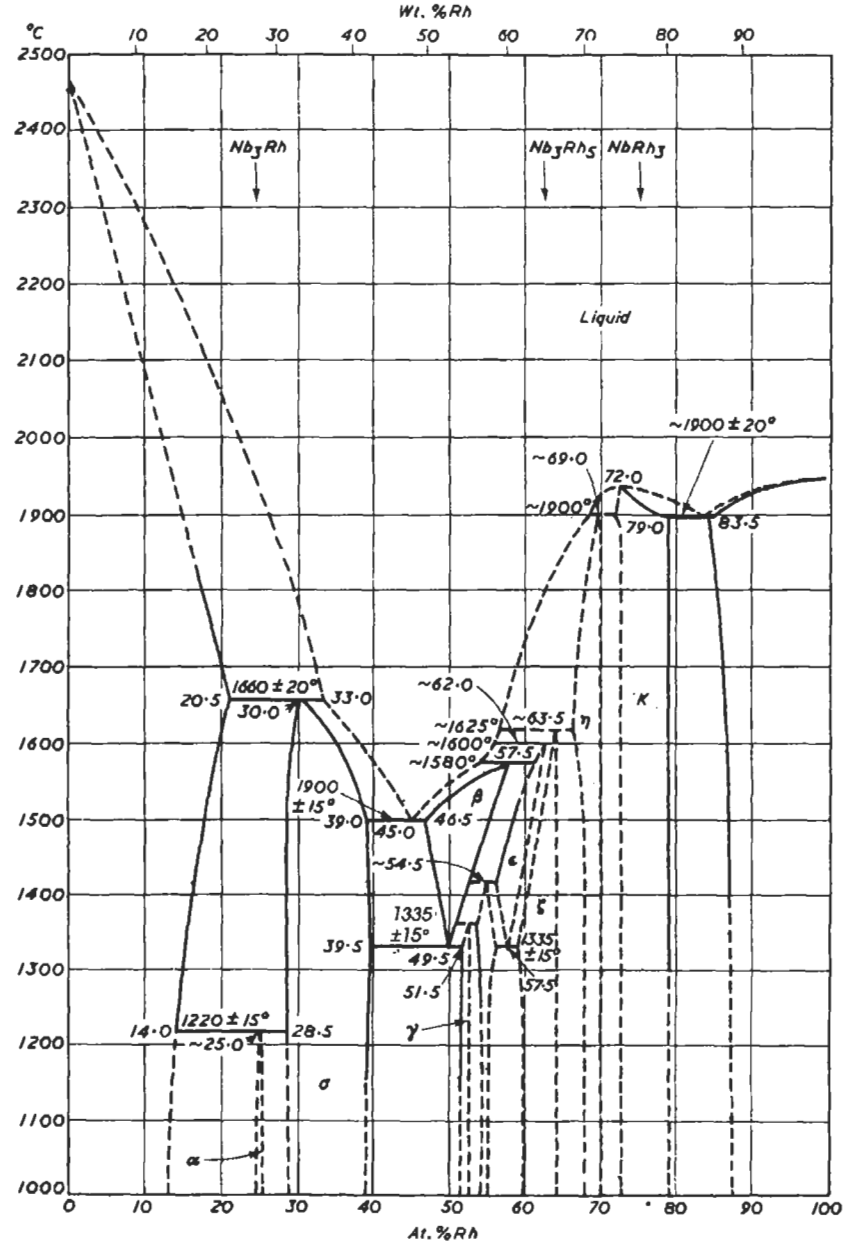
Nb–Os


°C
Wt % Os
Nb
10
20
30
40
50
60
70
80
90
Os
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
3033°C
Liquid
2469°C
2200°C
2270°C
19
2175°C
29
47
63
73
46
2120°C
(Os)
17
1975°C
27
(Nb)
α
β
χ
0
10
20
30
40
50
60
70
80
90
100
At % Os

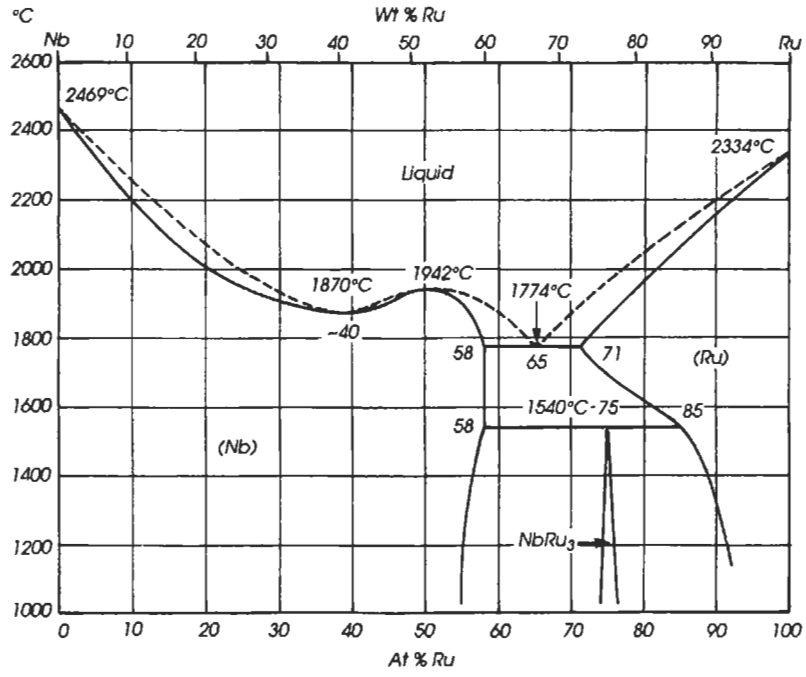
Nb–Re


°C
3400
3000
2600
2200
1800
1400
1000
600
Liquid
α+L
α+σ
σ
χ
αNb
α+χ
χ
χ + Re
0 10 20 30 40 50 60 70 80 90 100
At. % Re

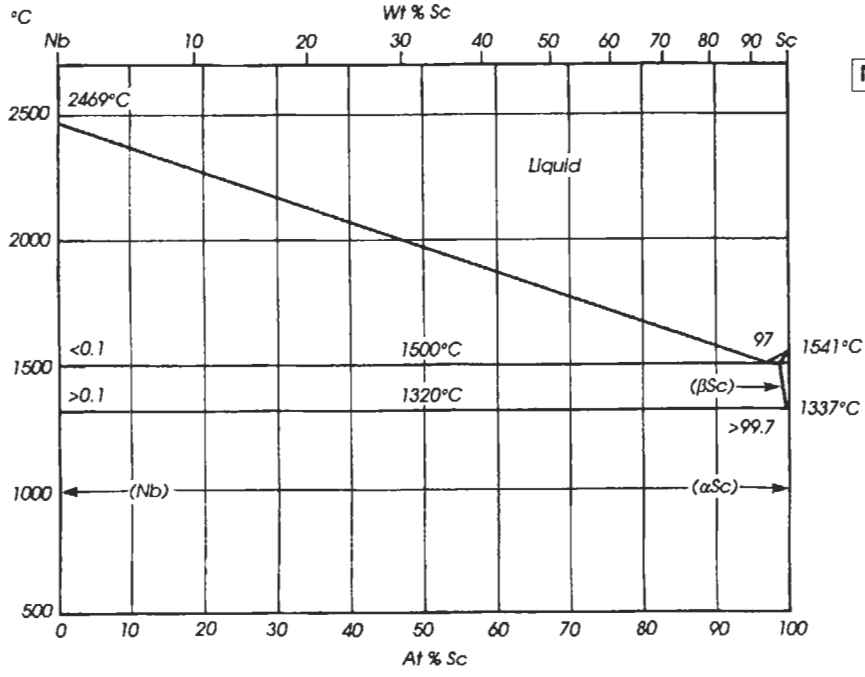
Nb–Rh


Wt. % Rh
°C
10 20 30 40 50 60 70 80 90
2500
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Nb3Rh
Nb3Rh5
NbRh3
Liquid
~1900 ± 20°
~69·0
72·0
~1900°
79·0
83·5
1660 ± 20°
20·5
30·0
33·0
~62·0
~1625°
~63·5
η
K
~1600°
57·5
~1580°
1900 ± 15°
39·0
45·0
46·5
β
~54·5
ε
ζ
1335 ± 15°
39·5
49·5
51·5
γ
1220 ± 15°
14·0
~25·0
28·5
σ
α
0 10 20 30 40 50 60 70 80 90 100
At. % Rh

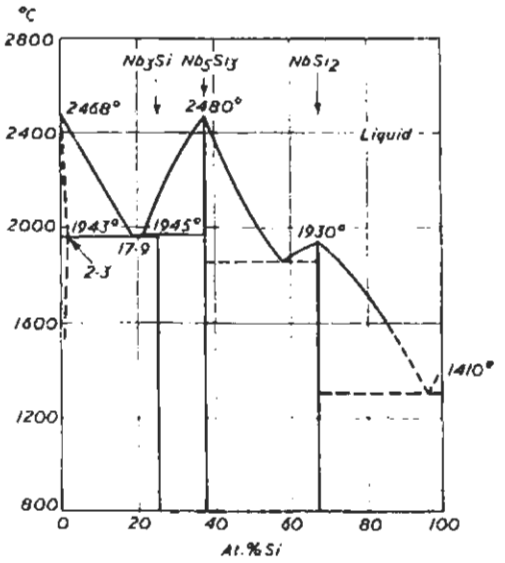
Nb–Ru


°C
Wt % Ru
Nb
Ru
2469°C
Liquid
2334°C
1870°C
1942°C
1774°C
~40
58
65
71
(Ru)
1540°C
75
85
58
(Nb)
NbRu3
At % Ru

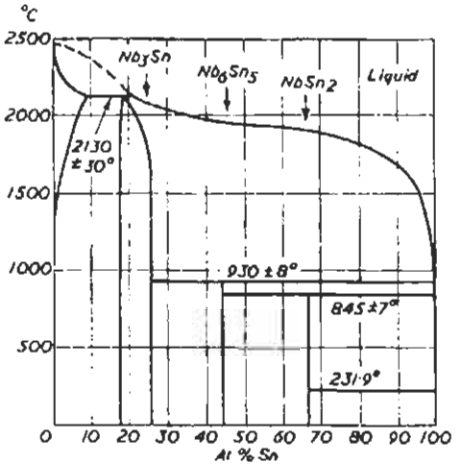
Nb–Sc

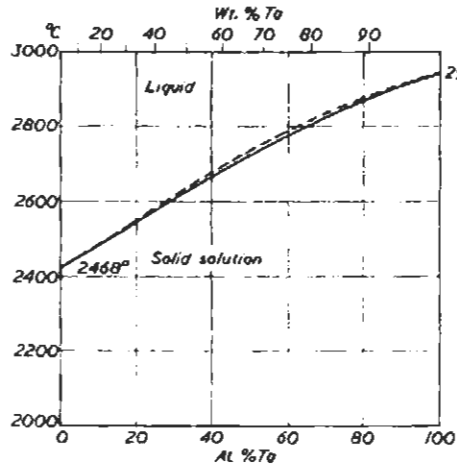

°C
Wt % Sc
Nb
Sc
2469°C
Liquid
<0.1
1500°C
97
1541°C
(βSc)
>0.1
1320°C
1337°C
>99.7
(Nb)
(αSc)
At % Sc

Nb–Si

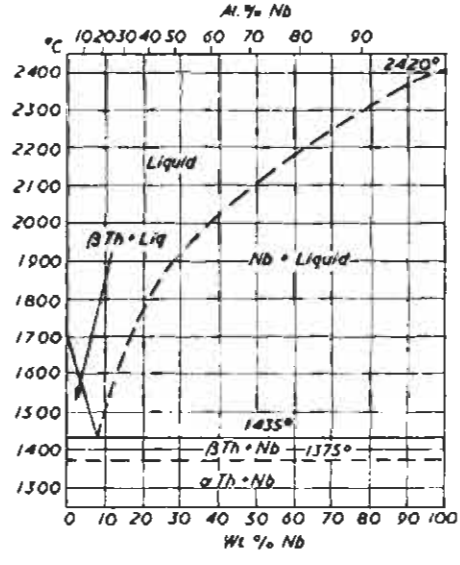

°C
2800
2400
2000
1600
1200
800
Nb3Si
Nb5Si3
NbSi2
2468°
2480°
Liquid
1943°
1945°
17·9
2·3
1930°
1410°
0
20
40
60
80
100
At.% Si

Nb–Sn

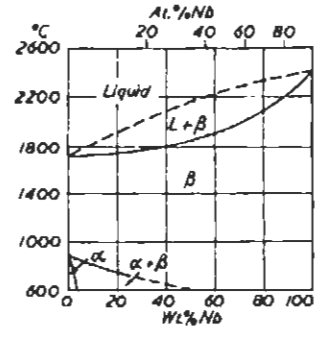

°C
2500
2000
1500
1000
500
Nb3Sn
Nb6Sn5
NbSn2
Liquid
2130
± 30°
930 ± 8°
845 ± 7°
231·9°
0
10
20
30
40
50
60
70
80
90
100
At % Sn



Nb–Ta

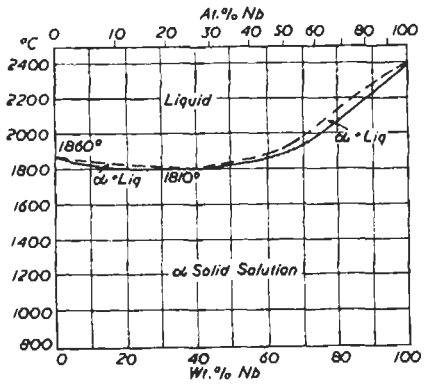


Nb–Th

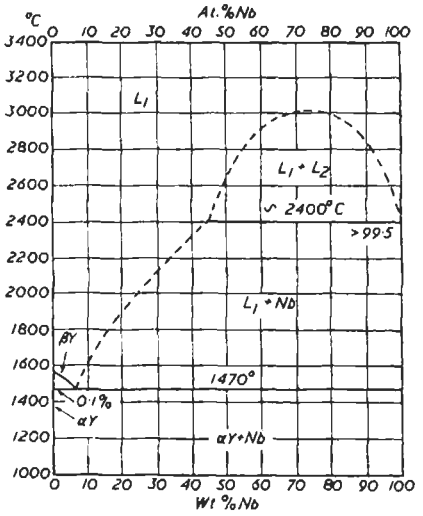


Nb–Ti

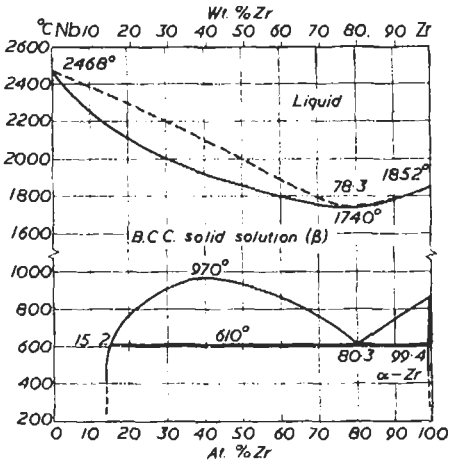
Nb–V



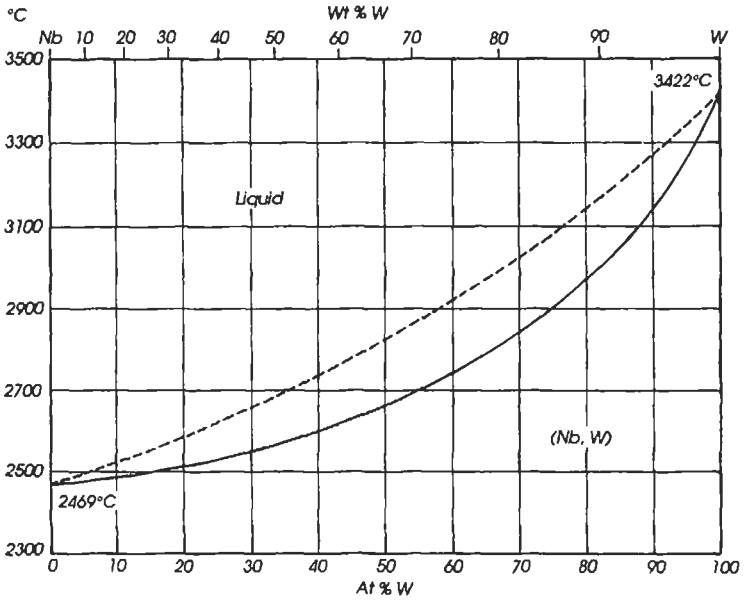
Nb–Y



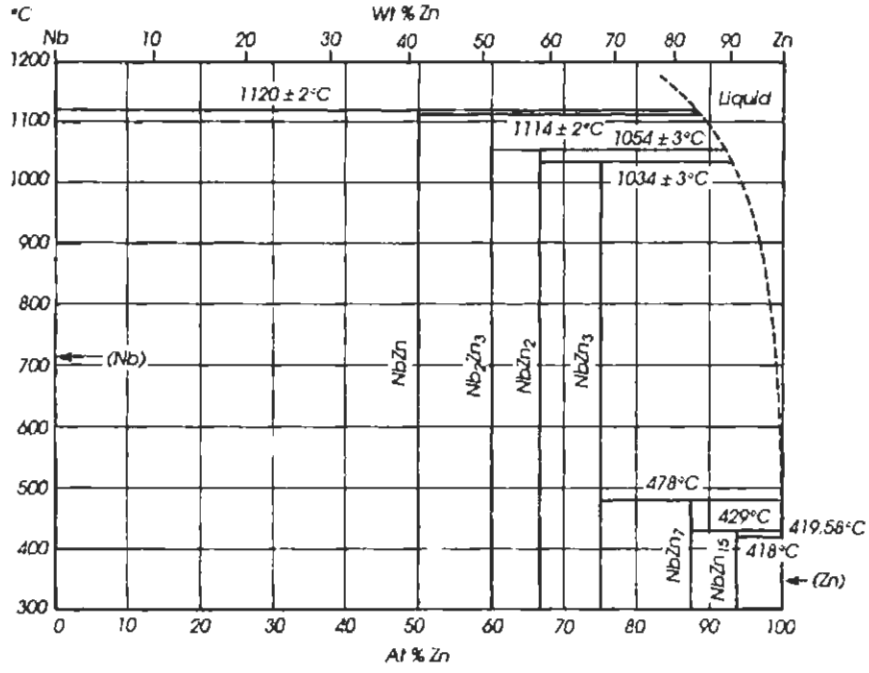
Nb–Zr



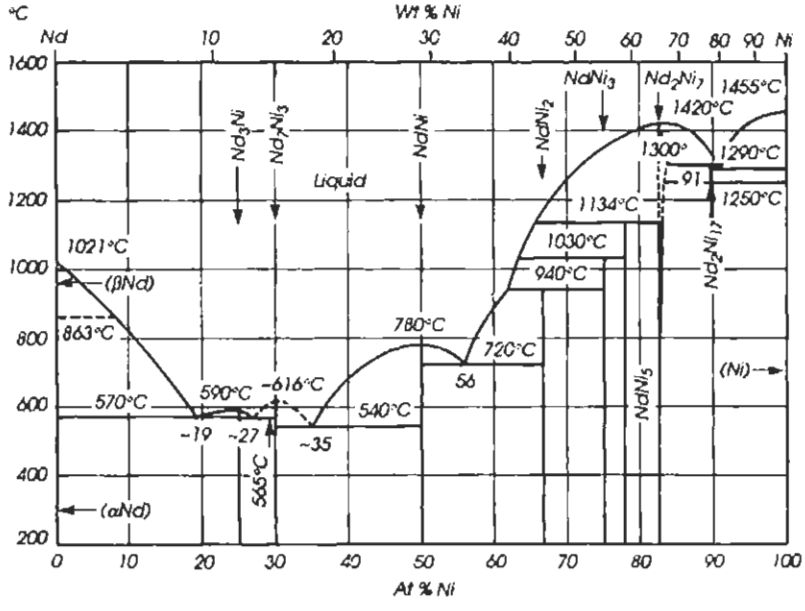
Nb–W



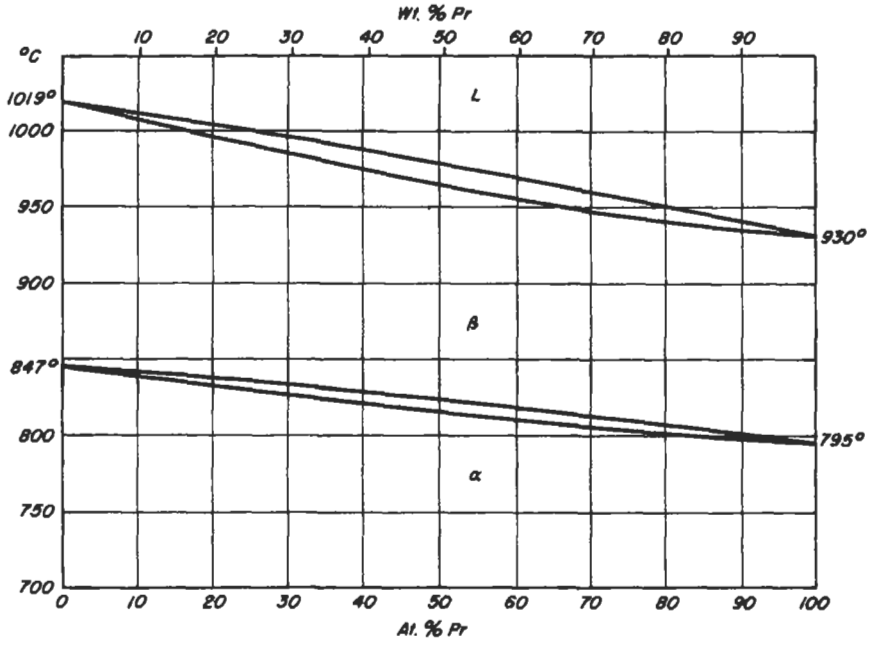
Nb–Zn


°C
Wt % Zn
Nb
Zn
1120 ± 2°C
1114 ± 2°C
1054 ± 3°C
1034 ± 3°C
Liquid
(Nb)
NbZn
Nb2Zn3
NbZn2
NbZn3
478°C
429°C
419.58°C
418°C
NbZn7
NbZn15
(Zn)
At % Zn

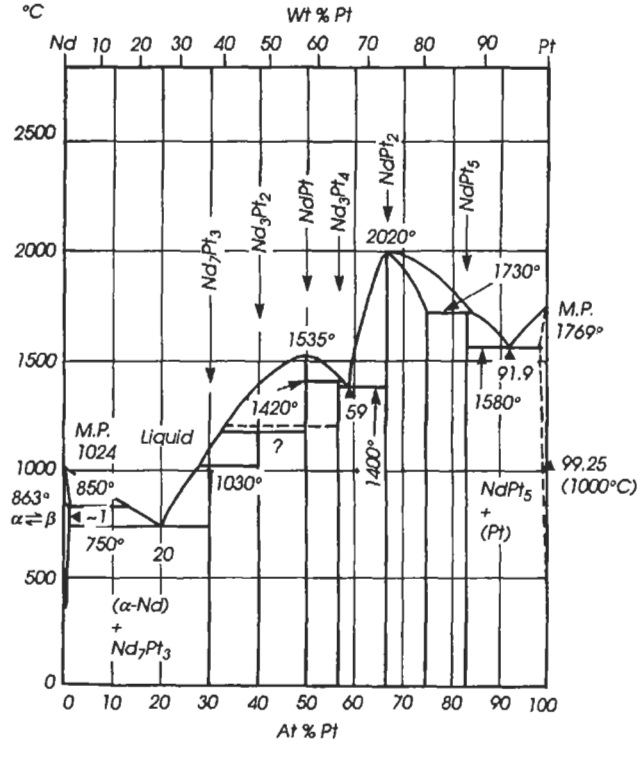
Nd–Ni


°C
Wt % Ni
Nd
Ni
Nd3Ni
Nd7Ni3
NdNi
NdNi2
NdNi3
Nd2Ni7
1455°C
1420°C
1300°
1290°C
91
1250°C
Liquid
1134°C
1030°C
940°C
Nd2Ni17
1021°C
(βNd)
863°C
780°C
720°C
56
(Ni)
570°C
590°C
~616°C
540°C
~19
~27
~35
565°C
NdNi5
(αNd)
At % Ni

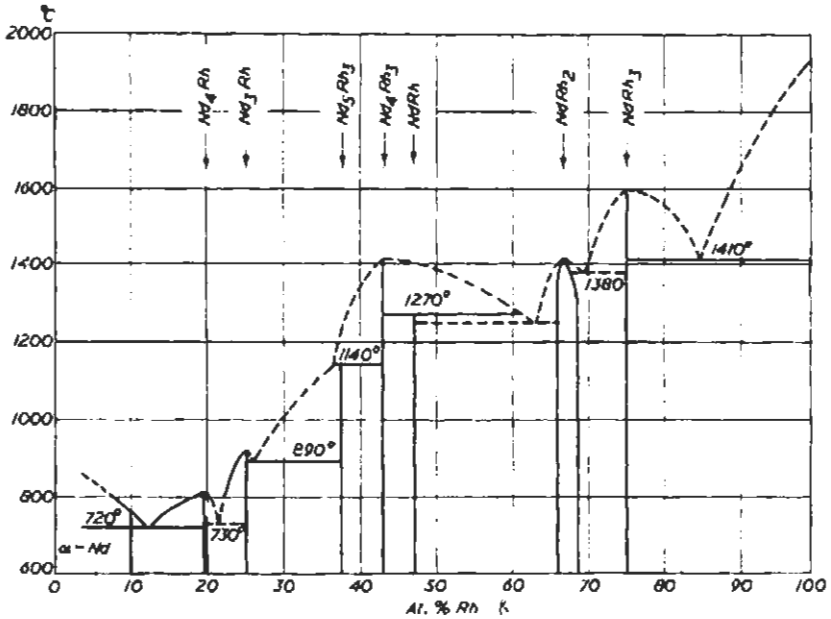
Nd–Pr


Wt. % Pr
°C
1019°
1000
950
900
847°
800
750
700
L
β
α
930°
795°
0 10 20 30 40 50 60 70 80 90 100
At. % Pr

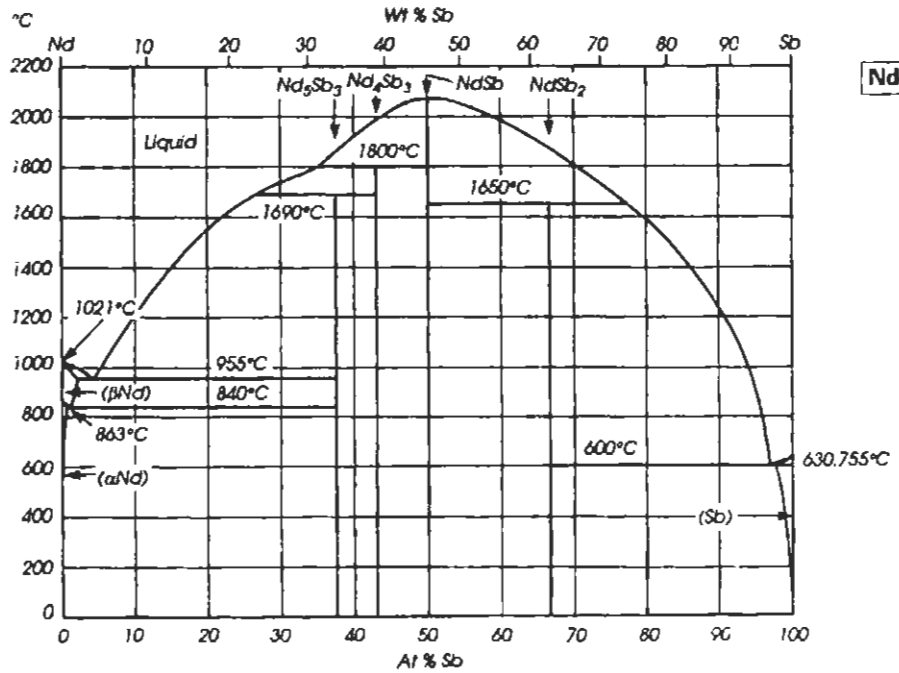
Nd–Pt


°C
Wt % Pt
Nd 10 20 30 40 50 60 70 80 90 Pt
2500
2000
1500
1000
500
0
Nd_7Pt_3
Nd_3Pt_2
NdPt
Nd_3Pt_4
$NdPt_2$
$NdPt_5$
2020°
1730°
M.P.
1769°
1535°
91.9
1580°
1420°
59
1400°
M.P.
1024
Liquid
?
1030°
850°
863°
α⇌β
~1
750°
20
99.25
(1000°C)
$NdPt_5$
+
(Pt)
(α-Nd)
+
Nd_7Pt_3
0 10 20 30 40 50 60 70 80 90 100
At % Pt

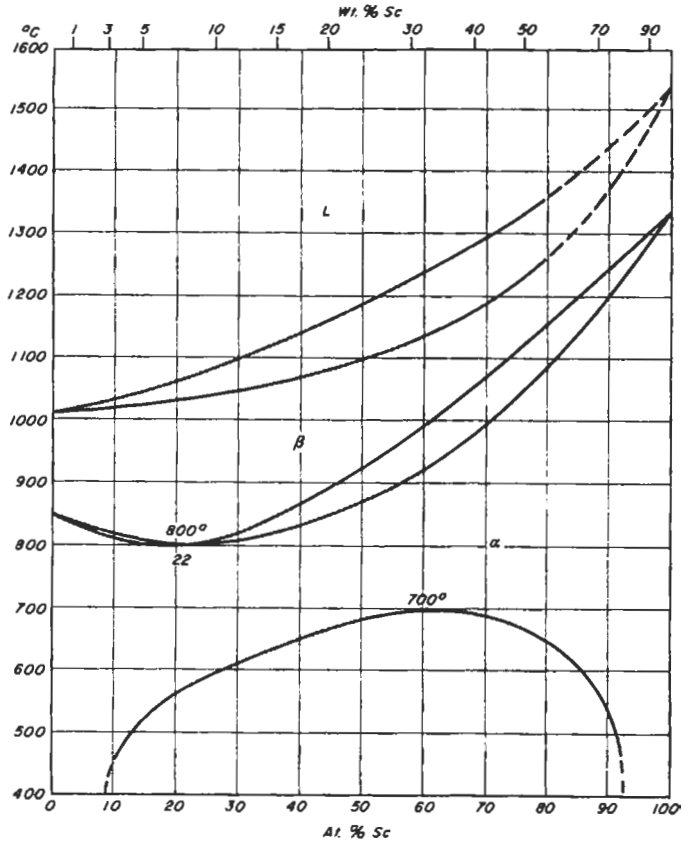
Nd–Rh


°C
2000
1800
1600
1400
1200
1000
800
600
NdRh
Nd2Rh3
Nd3Rh5
Nd5Rh4
NdRh
NdRh2
NdRh5
1410°
1380°
1270°
1140°
890°
730°
720°
α – Nd
0
10
20
30
40
50
60
70
80
90
100
At. % Rh

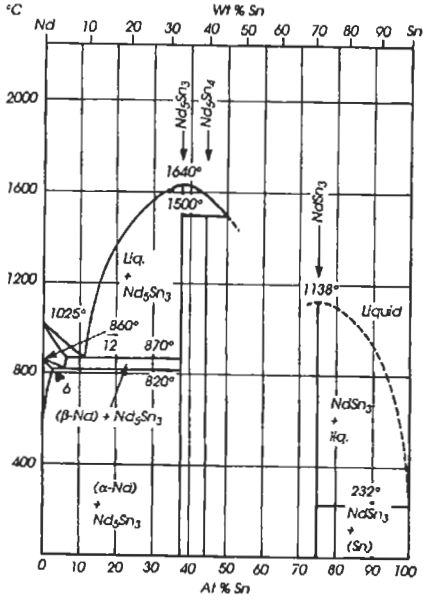
Nd–Sb


°C
Wt % Sb
Nd
10
20
30
40
50
60
70
80
90
Sb
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Nd5Sb3
Nd4Sb3
NdSb
NdSb2
Liquid
1800°C
1650°C
1690°C
1021°C
955°C
(βNd)
840°C
863°C
(αNd)
600°C
630.755°C
(Sb)
0
10
20
30
40
50
60
70
80
90
100
At % Sb

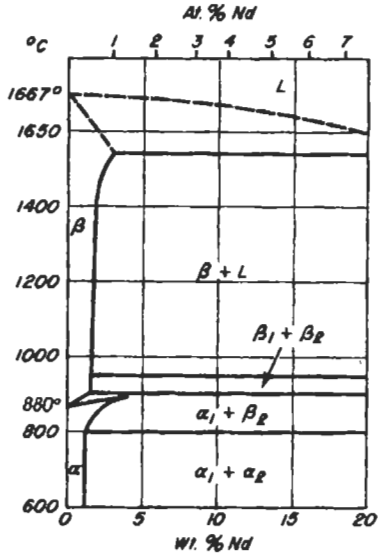
Nd–Sc


°C
Wt. % Sc
1 3 5 10 15 20 30 40 50 70 90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
L
β
α
800°
22
700°
0 10 20 30 40 50 60 70 80 90 100
At. % Sc

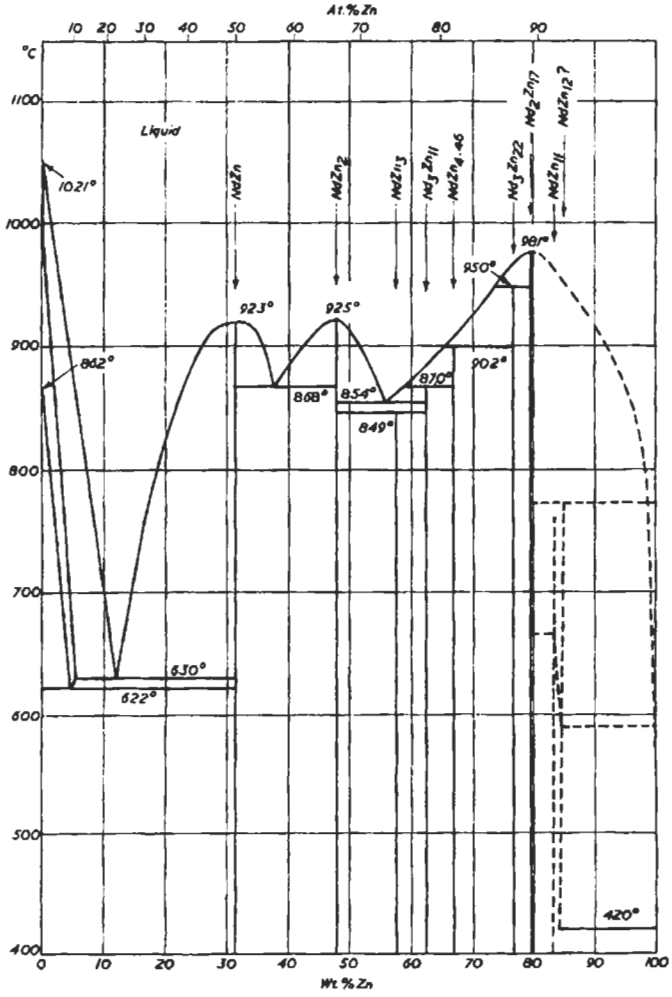
Nd–Sn


°C
Wt % Sn
Nd 10 20 30 40 50 60 70 80 90 Sn
2000
1600
1200
800
400
Nd_5Sn_3
Nd_5Sn_4
1640°
1500°
$NdSn_3$
Liq. + Nd_5Sn_3
1138°
Liquid
1025°
860°
12
870°
820°
δ
(β-Nd) + Nd_5Sn_3
$NdSn_3$ + liq.
(α-Nd) + Nd_5Sn_3
232°
$NdSn_3$ + (Sn)
0 10 20 30 40 50 60 70 80 90 100
At % Sn

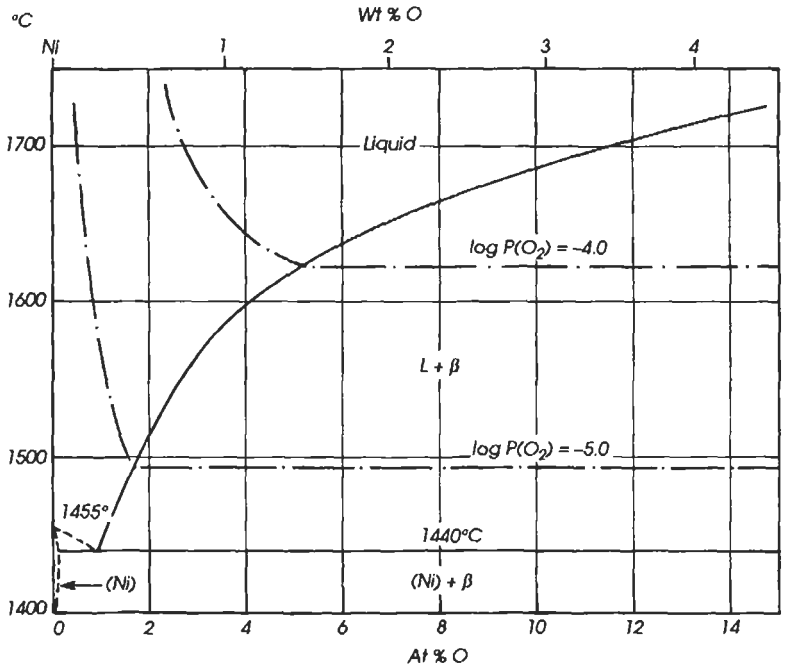
Nd–Ti


At. % Nd
°C
1 2 3 4 5 6 7
1667°
1650
1400
1200
1000
880°
800
600
L
β
β + L
β1 + β2
α1 + β2
α
α1 + α2
0 5 10 15 20
Wt. % Nd

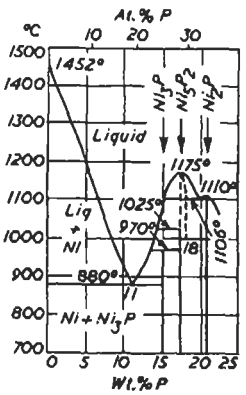
Nd–Zn


At. % Zn
10 20 30 40 50 60 70 80 90
°C
1100
1000
900
800
700
600
500
400
Liquid
1021°
842°
923°
925°
868°
854°
849°
870°
902°
950°
981°
630°
622°
NdZn
NdZn2
Nd11Zn10
Nd3Zn11
Nd13Zn58
Nd3Zn22
Nd2Zn17
NdZn11
NdZn12 ?
420°
0 10 20 30 40 50 60 70 80 90 100
Wt. % Zn

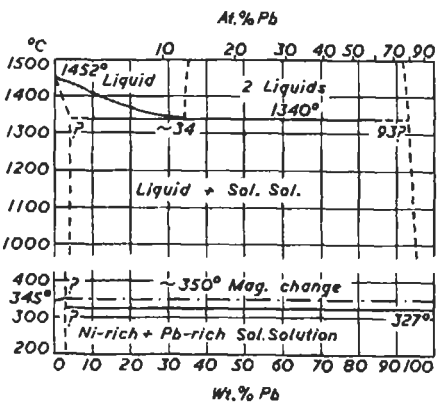
Ni–O


°C
Wt % O
Ni
1
2
3
4
1700
1600
1500
1400
Liquid
log P(O2) = -4.0
L + β
log P(O2) = -5.0
1455°
1440°C
(Ni)
(Ni) + β
0
2
4
6
8
10
12
14
At % O

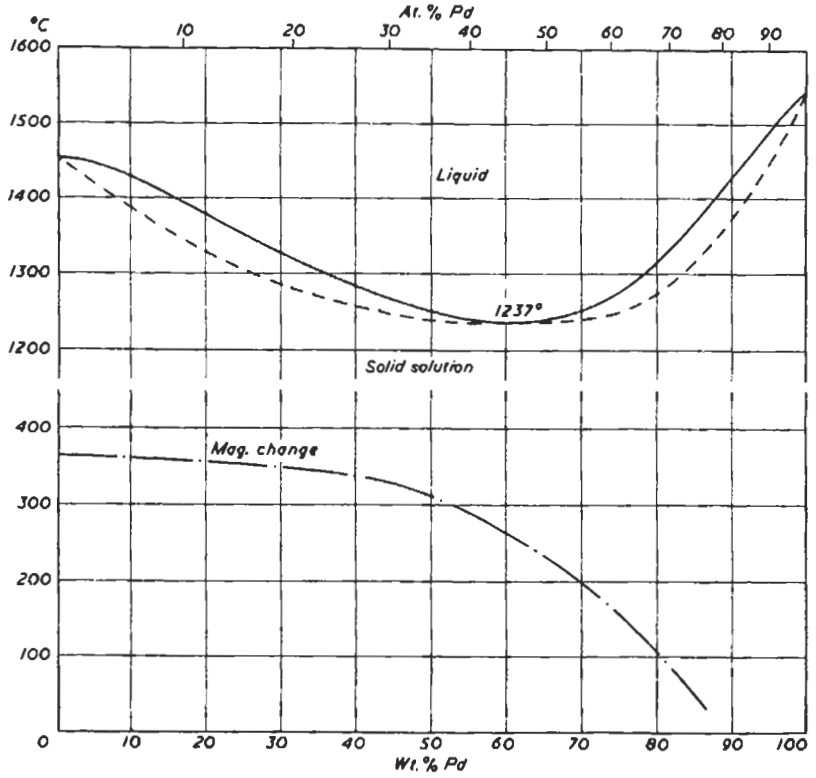
Ni–P


At. % P
°C
10
20
30
1500
1400
1300
1200
1100
1000
900
800
700
1452°
Liquid
Ni3P
Ni5P2
Ni2P
1175°
1110°
1025°
970°
Liq + Ni
880°
Ni + Ni3P
0
5
10
15
20
25
Wt.% P

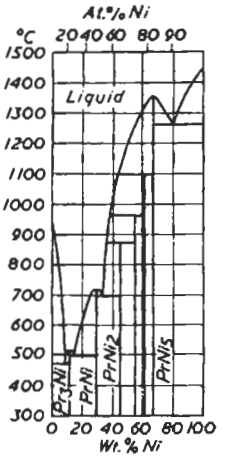
Ni–Pb


At.% Pb
°C
10
20
30
40
50
70
90
1500
1400
1300
1200
1100
1000
1452°
Liquid
2 Liquids
1340°
~34
937°
Liquid + Sol. Sol.
400
345°
300
200
~350° Mag. change
327°
Ni-rich + Pb-rich Sol. Solution
0
10
20
30
40
50
60
70
80
90
100
Wt.% Pb

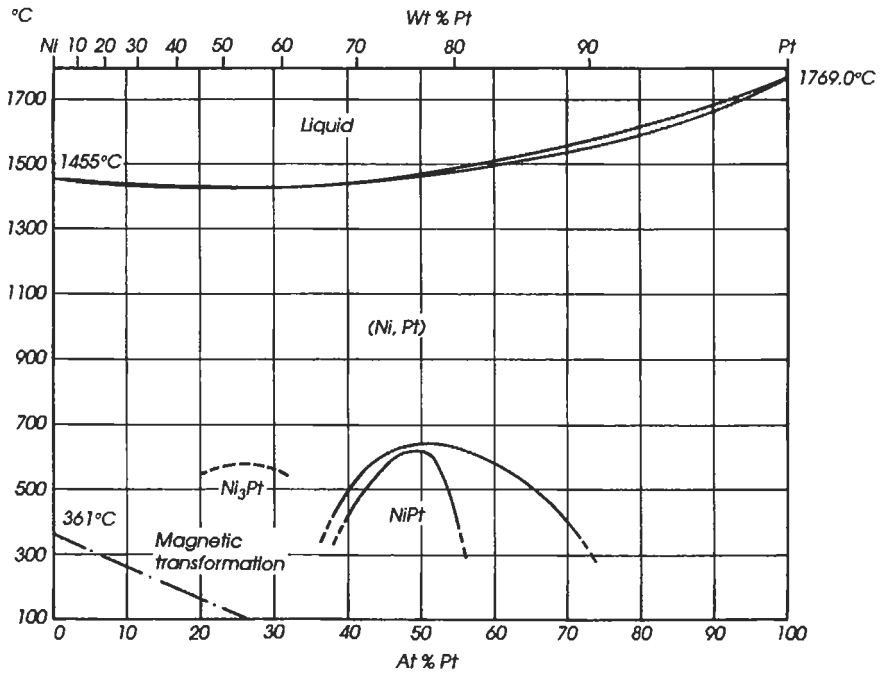
Ni–Pd


°C
At. % Pd
10 20 30 40 50 60 70 80 90
1600
1500
1400
1300
1200
Liquid
1237°
Solid solution
400
300
200
100
0
Mag. change
10 20 30 40 50 60 70 80 90 100
Wt. % Pd

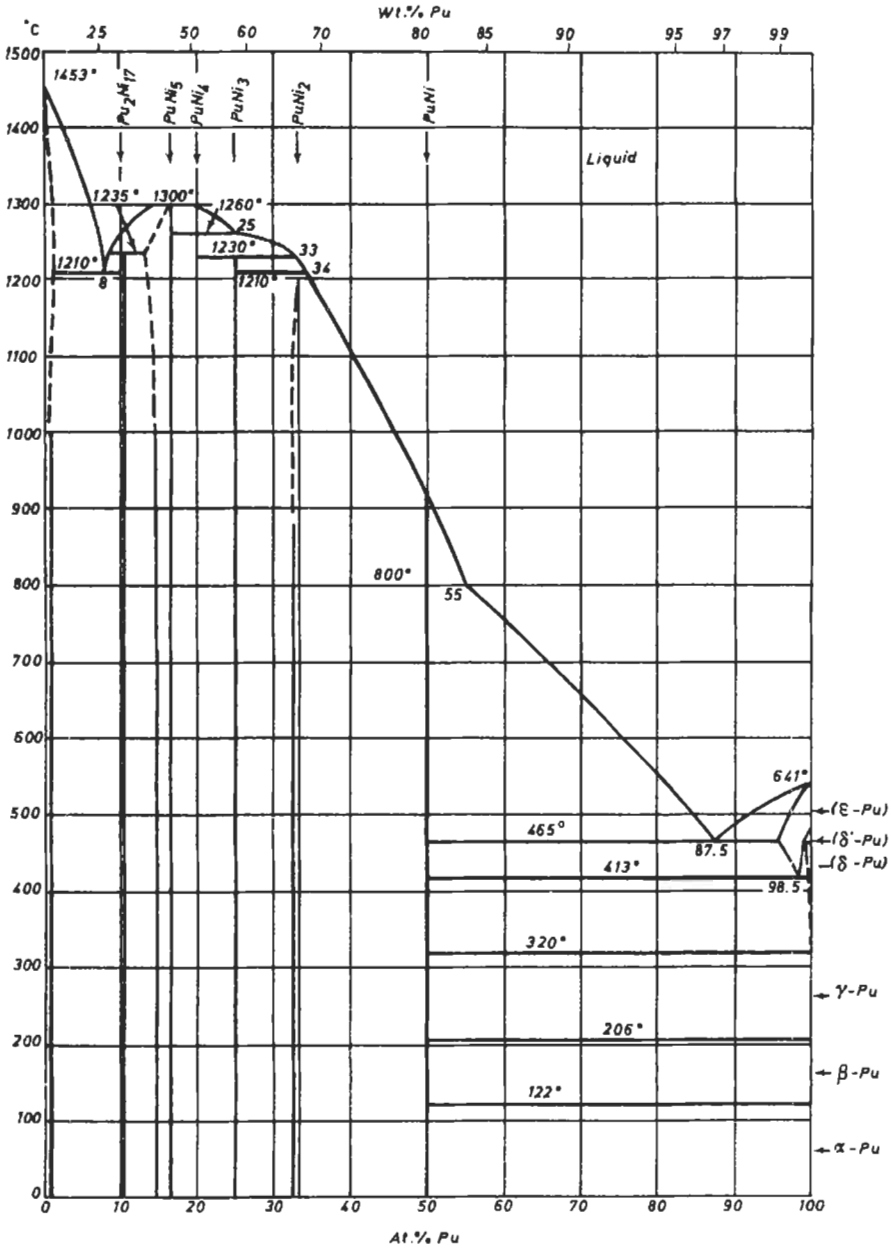
Ni–Pr


At.% Ni
°C
20 40 60 80 90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
Liquid
Pr3Ni
PrNi
PrNi2
PrNi5
0 20 40 60 80 100
Wt. % Ni

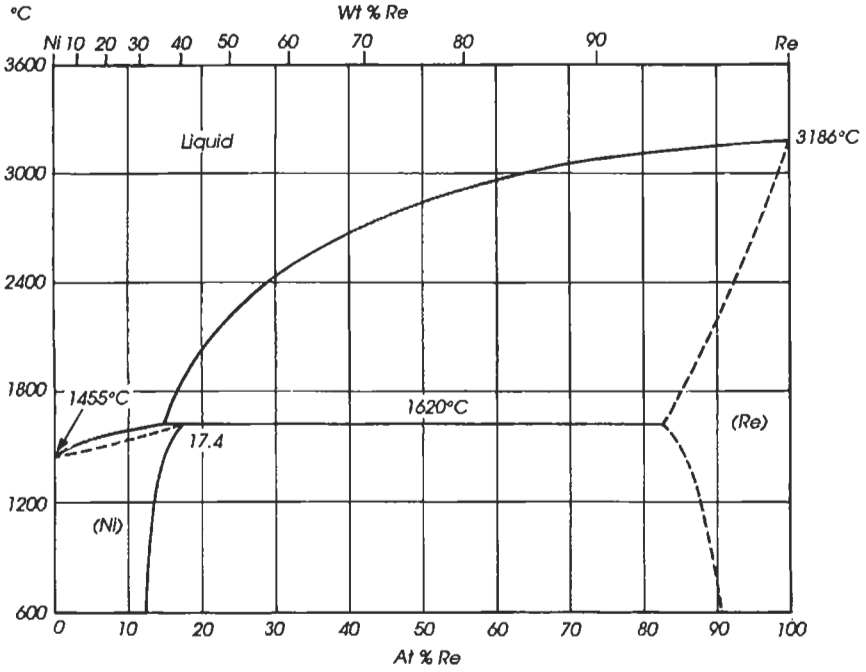
Ni–Pt


°C
Wt % Pt
Ni 10 20 30 40 50 60 70 80 90 Pt
1769.0°C
1700
1500
1300
1100
900
700
500
300
100
Liquid
1455°C
(Ni, Pt)
Ni3Pt
NiPt
361°C
Magnetic transformation
0 10 20 30 40 50 60 70 80 90 100
At % Pt

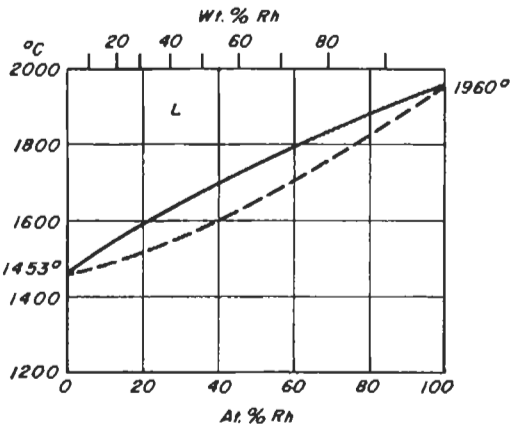
Ni–Pu


Wt.% Pu
°C
At.% Pu
Liquid
1453°
Pu_2Ni_{17}
PuNi5
$PuNi_4$
$PuNi_3$
$PuNi_2$
PuNi
1235°
1300°
1260°
25
1230°
33
34
1210°
8
1210°
800°
55
641°
(ε-Pu)
465°
(δ'-Pu)
87.5
413°
(δ-Pu)
98.5
320°
γ-Pu
206°
β-Pu
122°
α-Pu

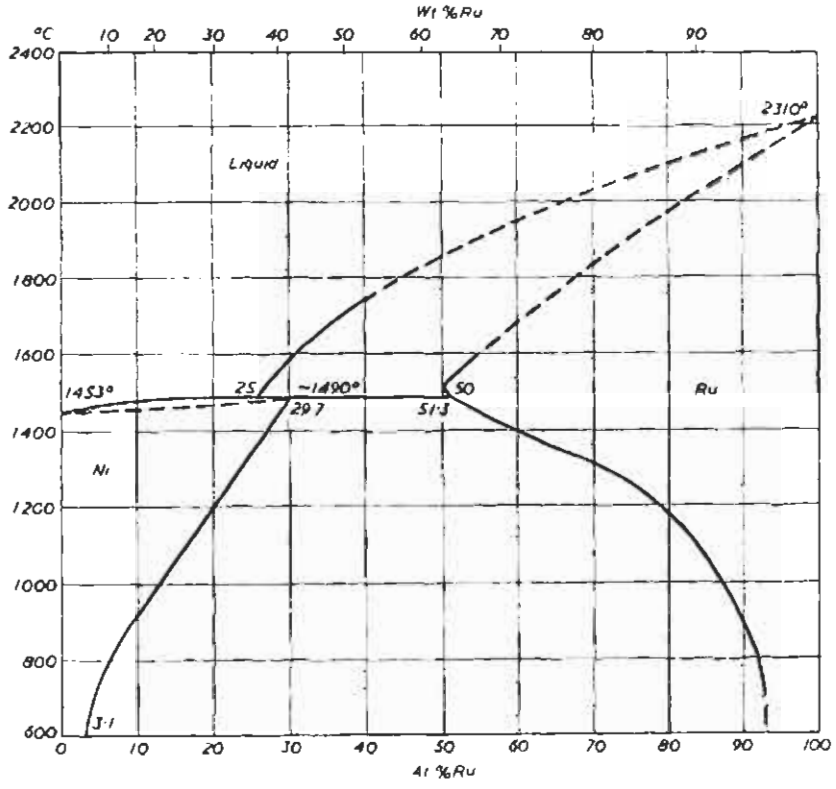
Ni–Re


°C
Wt % Re
Ni 10 20 30 40 50 60 70 80 90 Re
3600
3000
2400
1800
1200
600
Liquid
3186°C
1455°C
1620°C
17.4
(Re)
(Ni)
0 10 20 30 40 50 60 70 80 90 100
At % Re

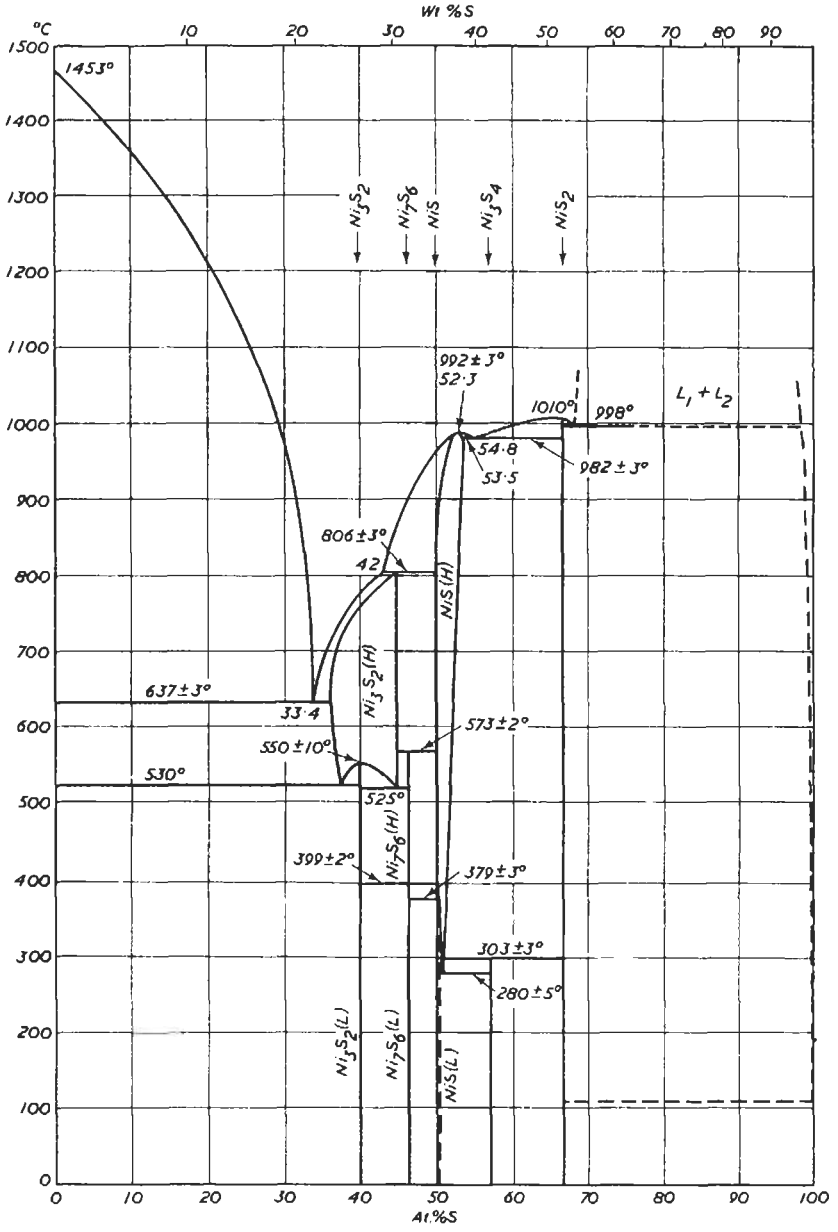
Ni–Rh


Wt. % Rh
°C
20 40 60 80
2000
1800
1600
1453°
1400
1200
L
1960°
0 20 40 60 80 100
At. % Rh

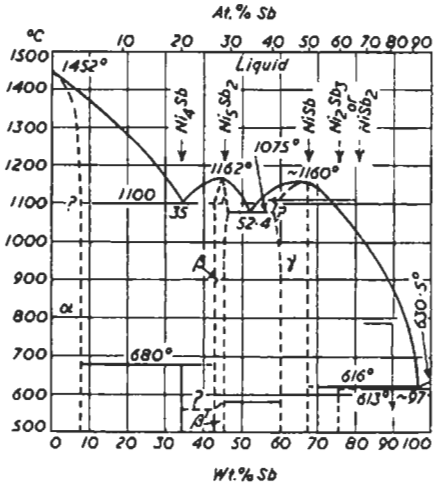
Ni–Ru


Wt %Ru
°C
10
20
30
40
50
60
70
80
90
2400
2200
2000
1800
1600
1400
1200
1000
800
600
LAquid
2310°
1453°
25
~1490°
50
29·7
51·3
Ni
Ru
3·1
0
10
20
30
40
50
60
70
80
90
100
At %Ru

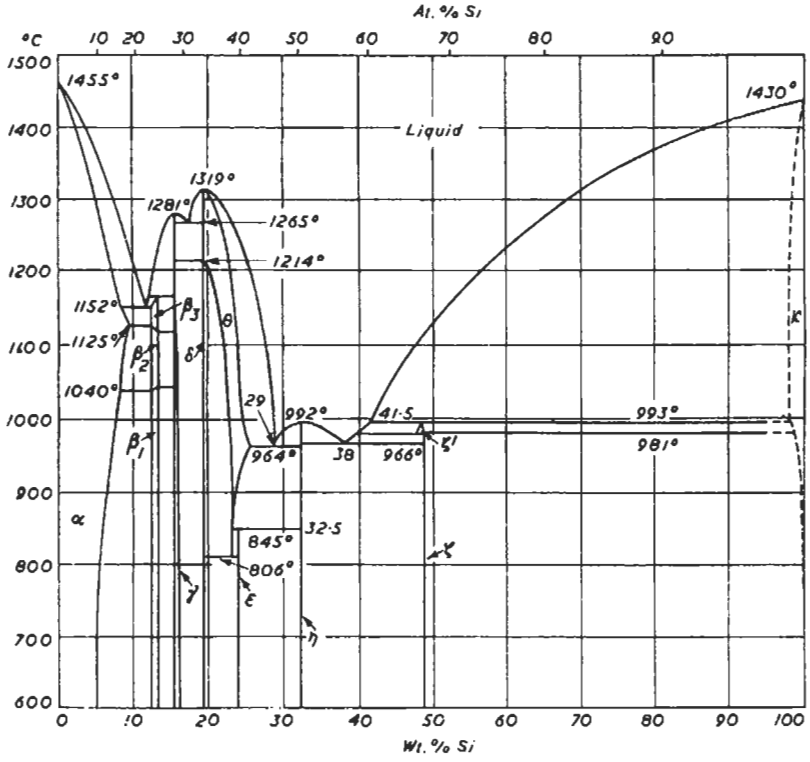
Ni–S


°C
Wt %S
At.%S
1453°
992 ± 3°
52·3
1010°
998°
$L_1 + L_2$
54·8
53·5
982 ± 3°
806 ± 3°
42
637 ± 3°
33·4
550 ± 10°
530°
525°
573 ± 2°
399 ± 2°
379 ± 3°
303 ± 3°
280 ± 5°
Ni_3S_2
Ni_7S_6
NiS
Ni_3S_4
NiS_2
$Ni_3S_2(H)$
$Ni_7S_6(H)$
NiS(H)
$Ni_3S_2(L)$
$Ni_7S_6(L)$
NiS(L)

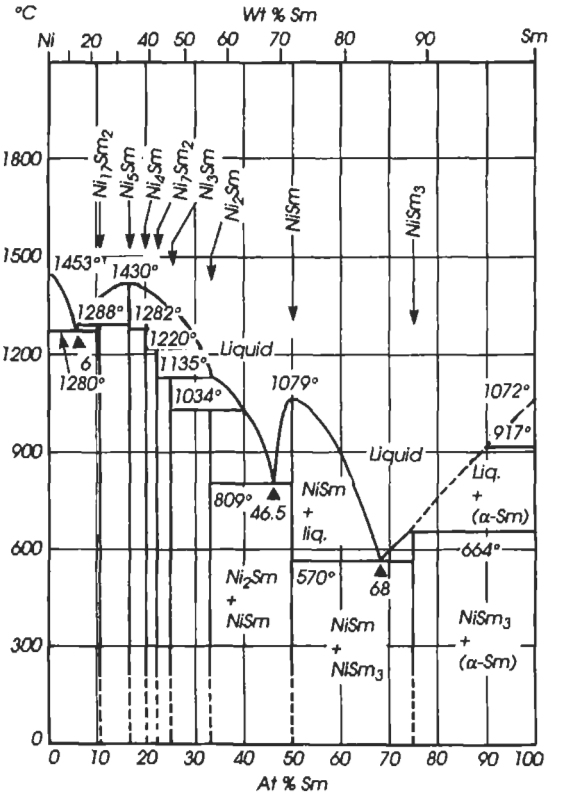
Ni–Sb


At. % Sb
°C
Liquid
1452°
Ni3Sb
Ni5Sb2
NiSb
Ni2Sb3 or NiSb2
1075°
1162°
~1160°
1100
35
52·4
630·5°
680°
616°
613°
~97
α
β
γ
δ
ζ
Wt. % Sb

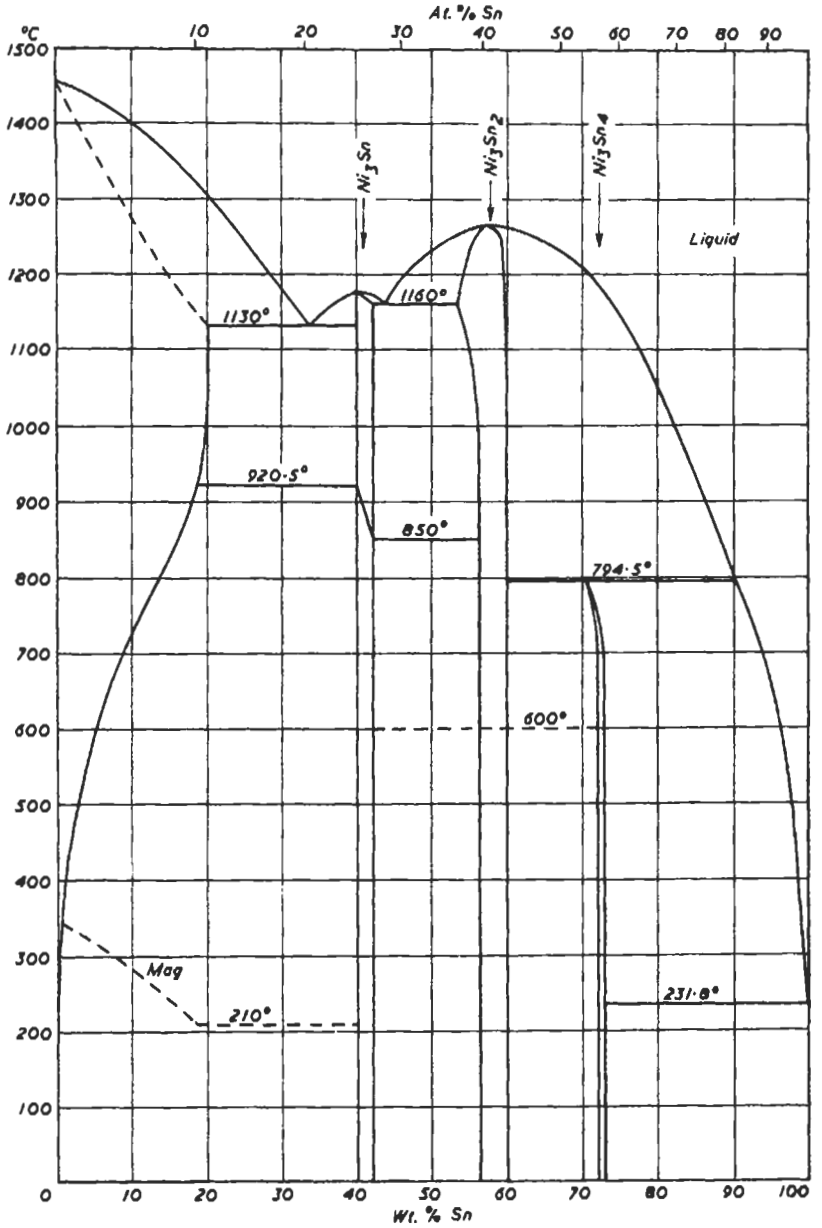
Ni–Si


At. % Si
°C
Liquid
1455°
1430°
1319°
1281°
1265°
1214°
1152°
1125°
1040°
992°
964°
966°
993°
981°
845°
806°
32·5
41·5
29
38
α
β1
β2
β3
γ
δ
ε
ζ
η
θ
κ
Wt. % Si

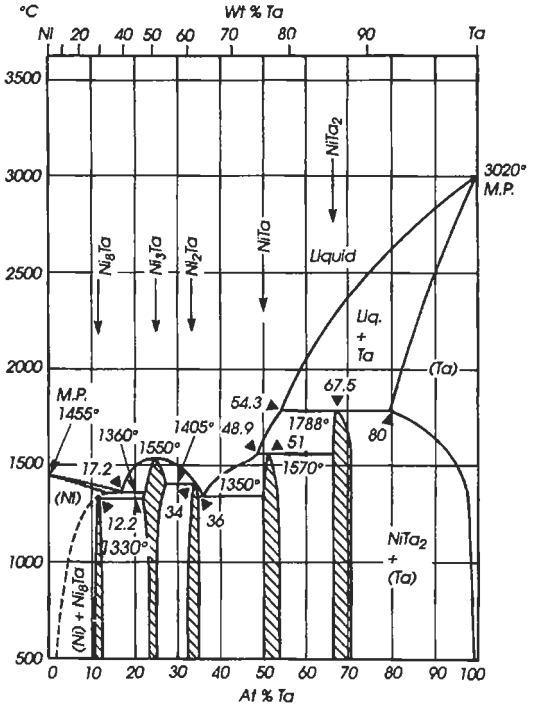
Ni–Sm


°C
Wt % Sm
Ni
20
40
50
60
70
80
90
Sm
1800
1500
1200
900
600
300
0
$Ni_{17}Sm_2$
Ni_5Sm
Ni_4Sm
Ni_7Sm_2
Ni_3Sm
Ni_2Sm
NiSm
$NiSm_3$
1453°
1430°
1288°
1282°
1220°
Liquid
1135°
1034°
1280°
δ
1079°
1072°
917°
Liquid
Liq.
+
(α-Sm)
809°
46.5
NiSm
+
liq.
664°
570°
68
Ni_2Sm
+
NiSm
NiSm
+
$NiSm_3$
$NiSm_3$
+
(α-Sm)
0
10
20
30
40
50
60
70
80
90
100
At % Sm

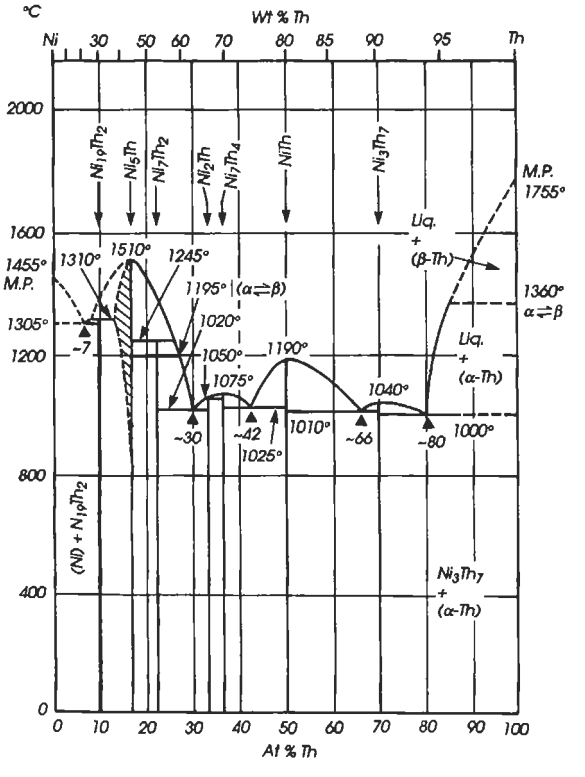
Ni–Sn


°C
At. % Sn
10
20
30
40
50
60
70
80
90
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Ni3Sn
Ni3Sn2
Ni3Sn4
Liquid
1130°
1160°
920·5°
850°
794·5°
600°
Mag
210°
231·8°
Wt. % Sn

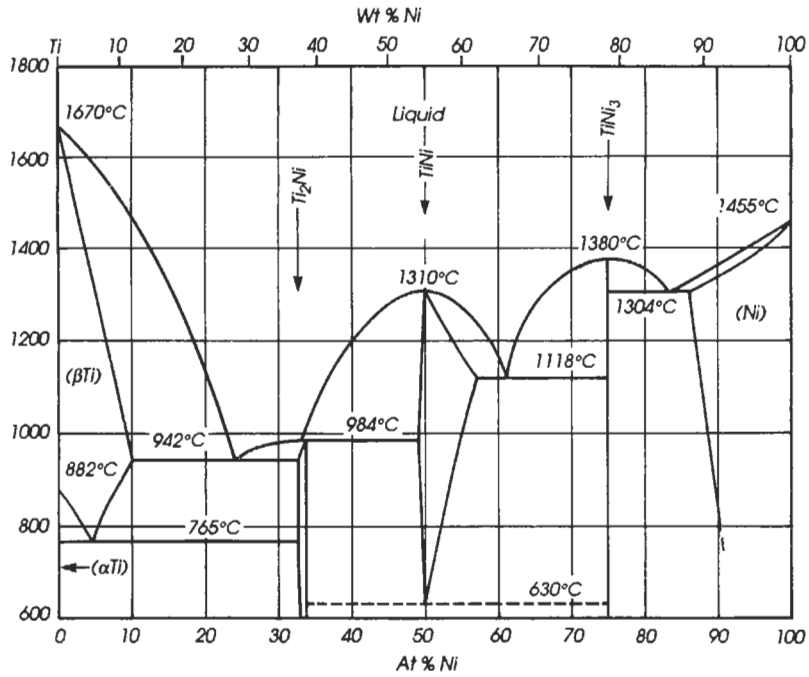
Ni–Ta


°C
Wt % Ta
Ni
Ta
3500
3000
2500
2000
1500
1000
500
Ni_8Ta
Ni_3Ta
Ni_2Ta
NiTa
$NiTa_2$
Liquid
3020°
M.P.
Liq.
+
Ta
(Ta)
M.P.
1455°
1360°
1550°
1405°
54.3
48.9
1788°
51
1570°
67.5
80
17.2
(Ni)
1350°
12.2
1330°
34
36
$NiTa_2$
+
(Ta)
(Ni) + Ni_8Ta
At % Ta

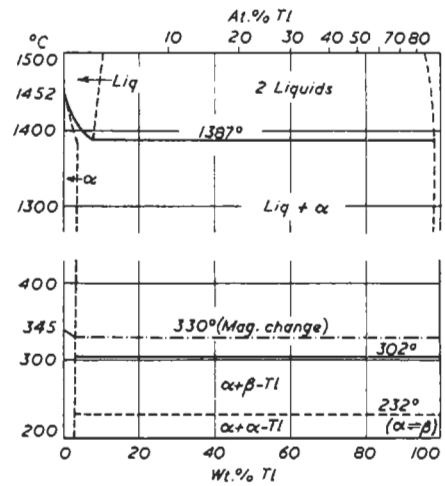
Ni–Th


°C
Wt % Th
Ni
Th
2000
1600
1200
800
400
0
$Ni_{19}Th_2$
Ni_5Th
Ni_7Th_2
Ni_2Th
Ni_7Th_4
NiTh
Ni_3Th_7
M.P.
1755°
Liq.
+
(β-Th)
1360°
α⇌β
Liq.
+
(α-Th)
1455°
M.P.
1310°
1510°
1245°
1195°
(α⇌β)
1305°
1020°
1200
1050°
1190°
1075°
1040°
~7
~30
~42
1025°
1010°
~66
~80
1000°
(Ni) + $Ni_{19}Th_2$
Ni_3Th_7
+
(α-Th)
At % Th

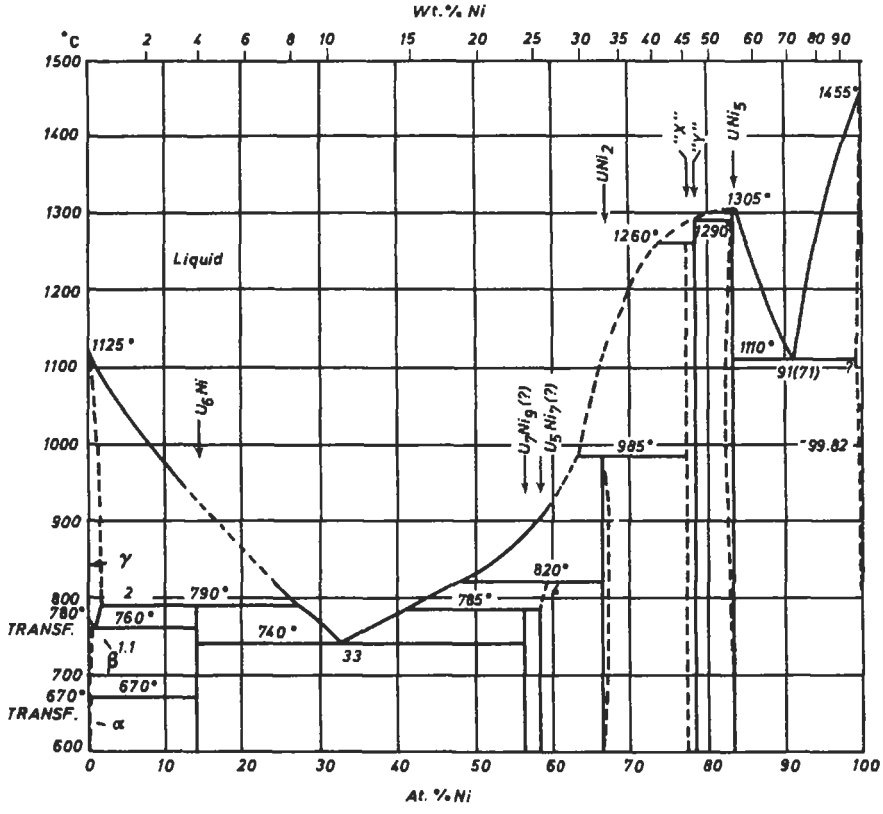
Ni–Ti


Wt % Ni
Ti
10
20
30
40
50
60
70
80
90
100
1800
1600
1400
1200
1000
800
600
1670°C
Liquid
Ti2Ni
TiNi
TiNi3
1455°C
1380°C
1310°C
1304°C
(Ni)
(βTi)
1118°C
984°C
942°C
882°C
765°C
(αTi)
630°C
At % Ni

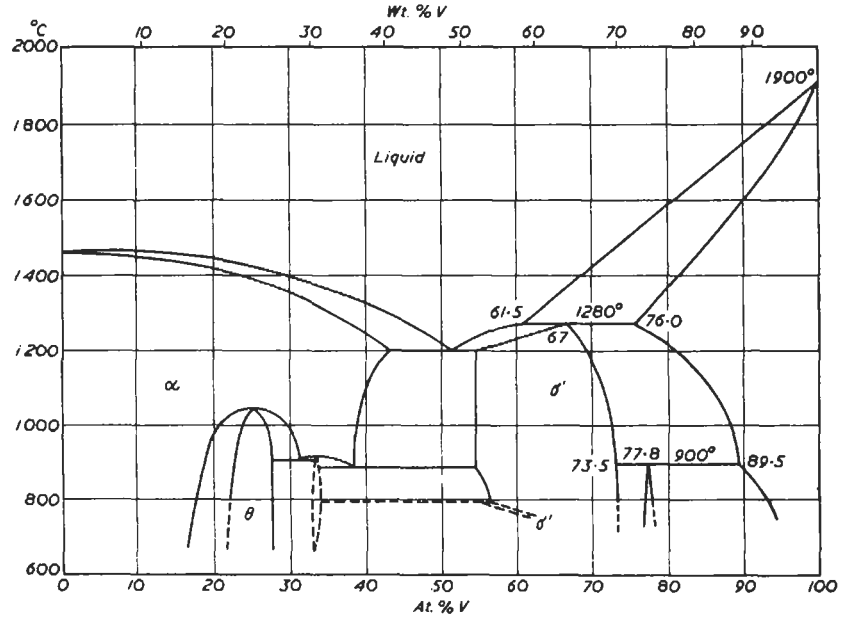
Ni–Tl

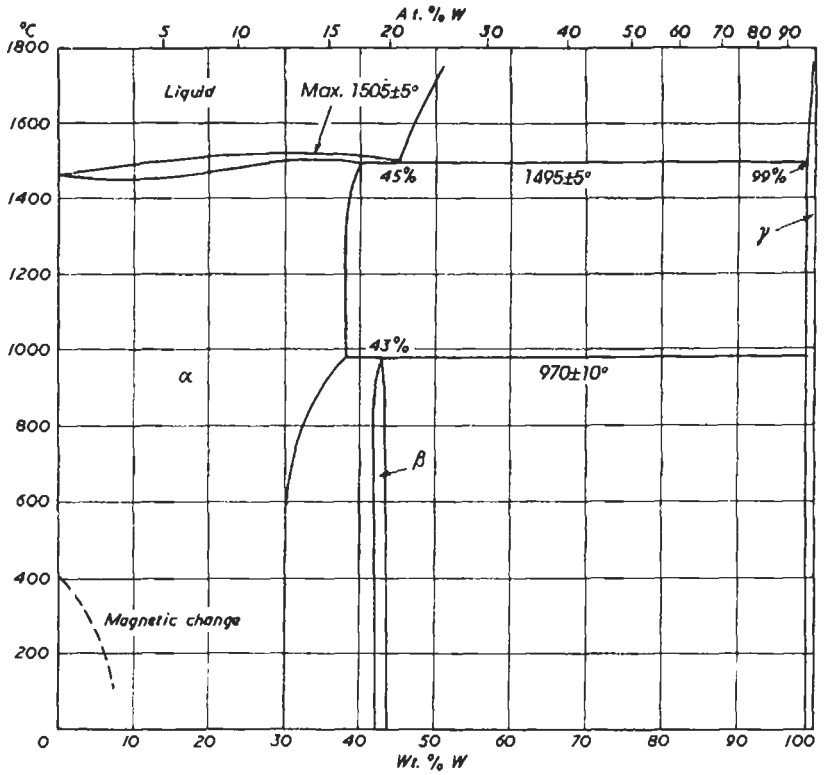

At.% Tl
°C
10
20
30
40
50
70
80
1500
1452
1400
1300
Liq
2 Liquids
1387°
α
Liq + α
400
345
300
200
330°(Mag. change)
302°
α+β-Tl
232°
(α=β)
α+α-Tl
0
20
40
60
80
100
Wt.% Tl

Ni–U

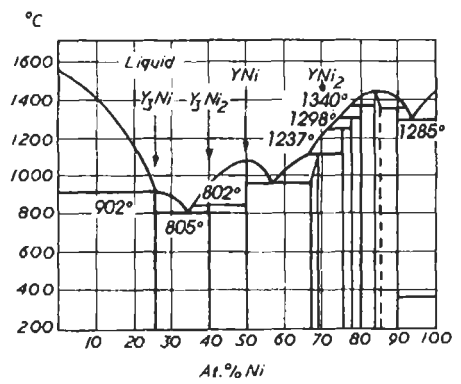

Wt.% Ni
°C
2 4 6 8 10 15 20 25 30 35 40 45 50 60 70 80 90
1500
1400
1300
1200
1100
1000
900
800
780°
700
670°
600
Liquid
1125°
U_6Ni
UNi_2
"X"
"Y"
UNi_5
1455°
1305°
1260°
1290°
1110°
91(71)
U_7Ni_9(?)
U_5Ni_7(?)
985°
99.82
γ
2
790°
760°
TRANSF.
740°
33
785°
820°
1.1
β
670°
TRANSF.
α
0 10 20 30 40 50 60 70 80 90 100
At. % Ni

Ni–V

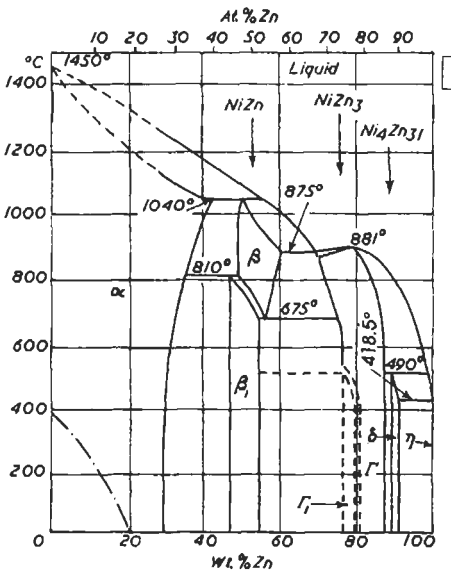

Wt. % V
°C
10 20 30 40 50 60 70 80 90
2000
1800
1600
1400
1200
1000
800
600
Liquid
1900°
61·5
1280°
76·0
67
α
δ'
73·5
77·8
900°
89·5
θ
δ'
0 10 20 30 40 50 60 70 80 90 100
At. % V


°C
At. % W
Liquid
Max. 1505±5°
45%
1495±5°
99%
γ
α
43%
970±10°
β
Magnetic change
Wt. % W

Ni–W

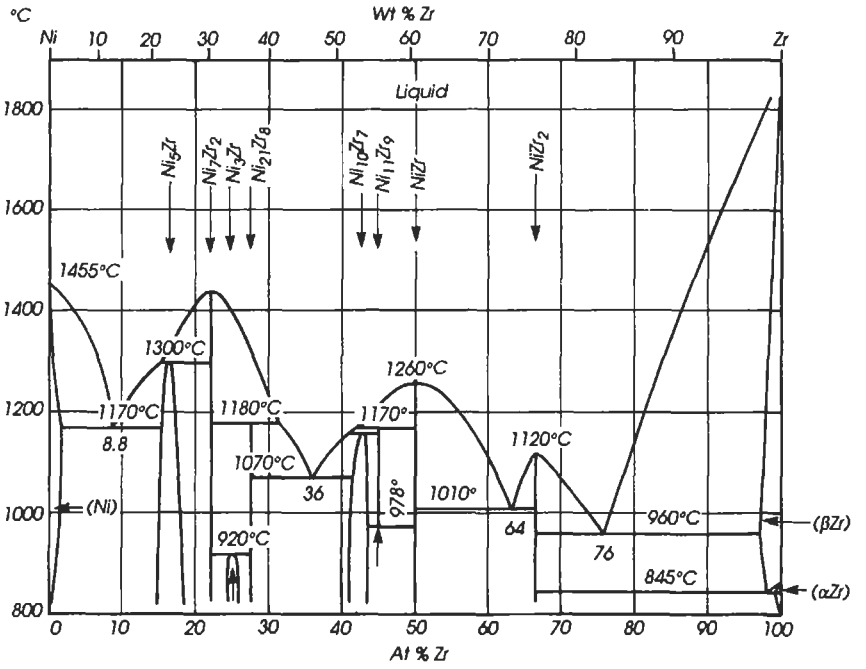

°C
Liquid
Y_3Ni
Y_3Ni_2
YNi
YNi_2
1340°
1298°
1237°
1285°
902°
805°
802°
At.% Ni

Ni–Y

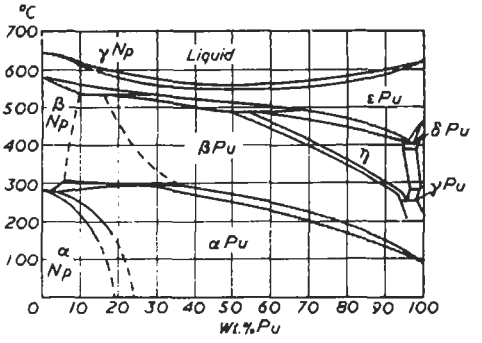

At.% Zn
°C
1450°
Liquid
NiZn
$NiZn_3$
Ni_4Zn_{31}
1040°
875°
881°
810°
β
α
675°
418.5°
490°
β_1
δ
η
Γ
Γ_1
Wt.% Zn

Ni–Zn

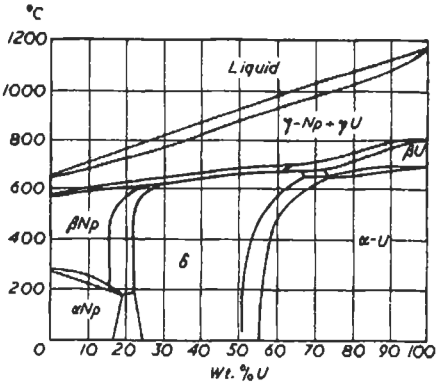
Nb–Zr


°C
Wt % Zr
Ni
Zr
Liquid
Ni5Zr
Ni7Zr2
Ni3Zr
Ni21Zr8
Ni10Zr7
Ni11Zr9
NiZr
NiZr2
1455°C
1300°C
1260°C
1180°C
1170°C
1170°C
1120°C
1070°C
1010°
978°
960°C
920°C
845°C
8.8
36
64
76
(Ni)
(βZr)
(αZr)
At % Zr

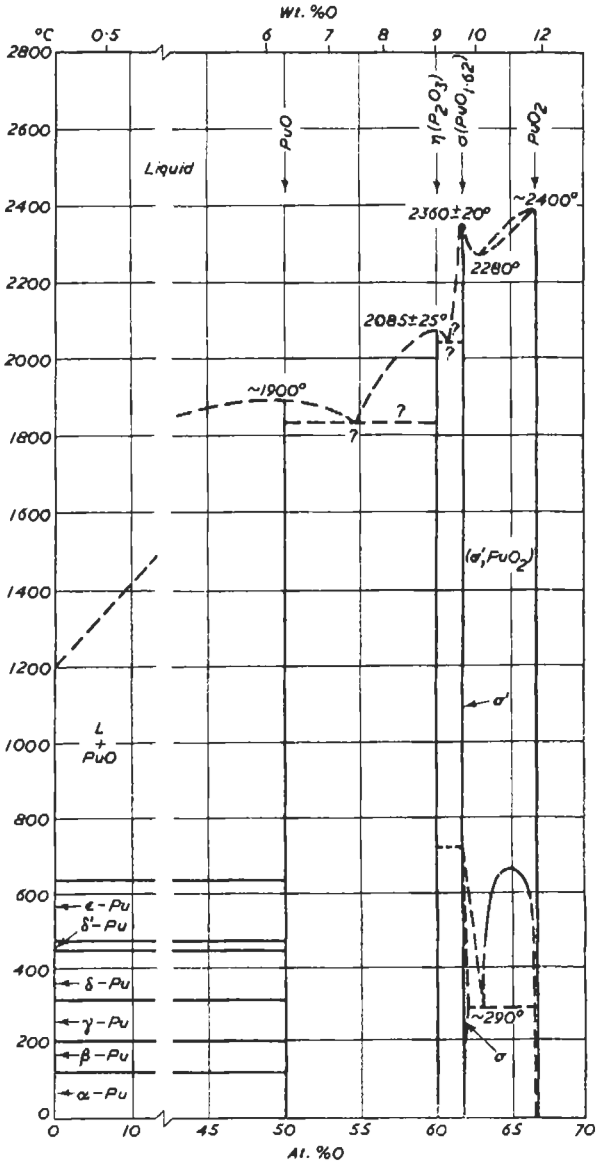
Np–Pu


°C
γ Np
Liquid
β Np
ε Pu
δ Pu
β Pu
η
γ Pu
α Pu
α Np
Wt.% Pu

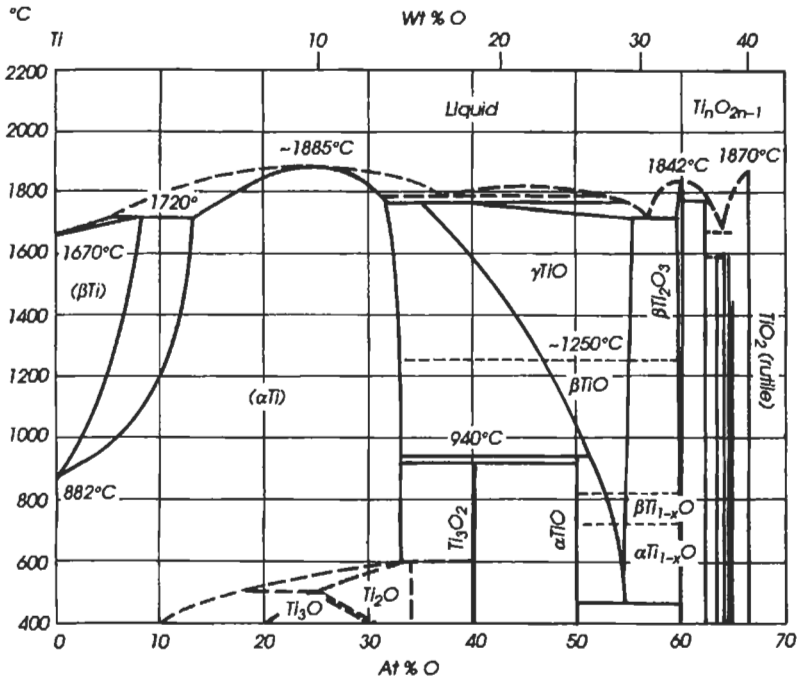
Np–U


°C
1200
1000
800
600
400
200
0
Liquid
γ-Np + γU
βU
βNp
δ
α-U
αNp
0 10 20 30 40 50 60 70 80 90 100
Wt. %U

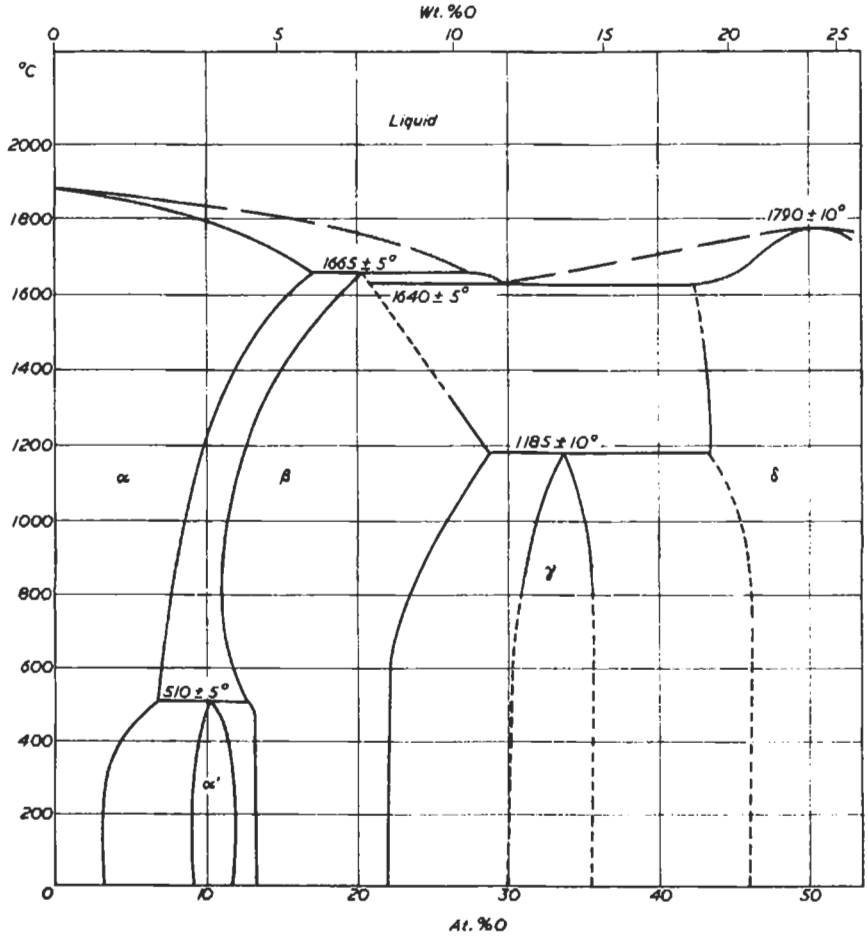
O–Pu


Wt. %O
°C
0·5
6
7
8
9
10
12
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Liquid
PuO
η(P2O3)
σ(PuO1.62)
PuO2
~2400°
2360±20°
2280°
2085±25°
~1900°
(σ',PuO2)
σ'
L + PuO
ε-Pu
δ'-Pu
δ-Pu
γ-Pu
β-Pu
α-Pu
~290°
σ
0 10 45 50 55 60 65 70
At. %O

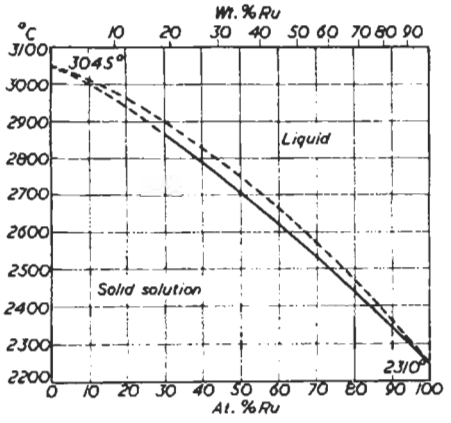
O–Ti


°C
Ti
Wt % O
10
20
30
40
2200
2000
1800
1600
1400
1200
1000
800
600
400
Liquid
Ti_nO_{2n-1}
~1885°C
1842°C
1870°C
1720°
1670°C
(βTi)
γTiO
$βTi_2O_3$
TiO_2 (rutile)
~1250°C
βTiO
(αTi)
940°C
882°C
Ti_3O_2
αTiO
$βTi_{1-x}O$
$αTi_{1-x}O$
Ti_2O
Ti_3O
0
10
20
30
40
50
60
70
At % O

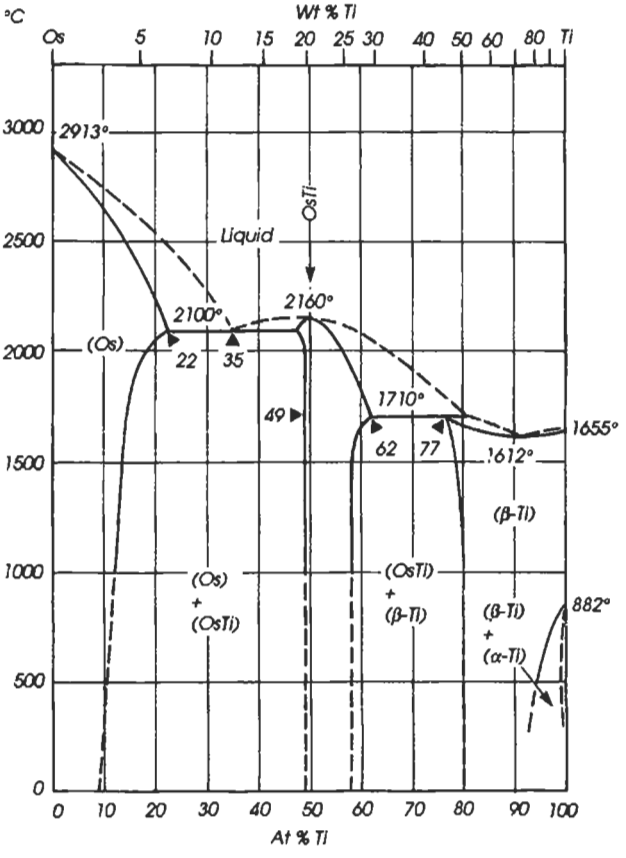
O–V


Wt. %O
0
5
10
15
20
25
°C
Liquid
2000
1800
1790 ± 10°
1665 ± 5°
1640 ± 5°
1600
1400
1200
1185 ± 10°
α
β
δ
γ
1000
800
600
510 ± 5°
400
α'
200
0
10
20
30
40
50
At. %O

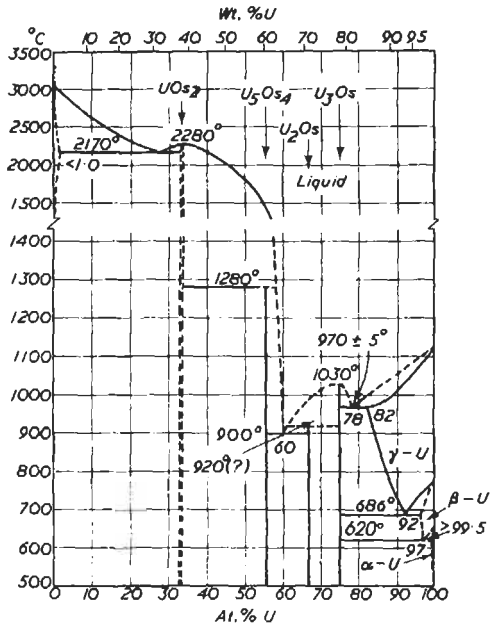
Os–Ru


Wt. % Ru
°C
10 20 30 40 50 60 70 80 90
3100
3000
2900
2800
2700
2600
2500
2400
2300
2200
3045°
Liquid
Solid solution
2310°
0 10 20 30 40 50 60 70 80 90 100
At. % Ru

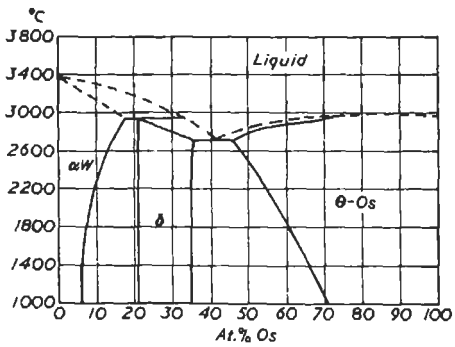
Os–Ti


°C
Wt % Ti
Os 5 10 15 20 25 30 40 50 60 80 Ti
3000
2500
2000
1500
1000
500
0
2913°
Liquid
OsTi
2160°
2100°
(Os)
22
35
49
1710°
62
77
1655°
1612°
(β-Ti)
(Os)
+
(OsTi)
(OsTi)
+
(β-Ti)
(β-Ti)
+
(α-Ti)
882°
0 10 20 30 40 50 60 70 80 90 100
At % Ti

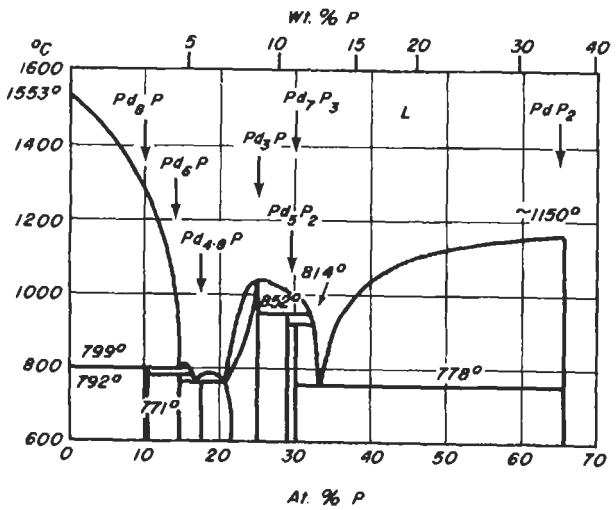
Os–U


Wt. %U
°C
10 20 30 40 50 60 70 80 90 95
3500
3000
2500
2000
1500
1400
1300
1200
1100
1000
900
800
700
600
500
UOs_2
U_5Os_4
U_3Os
U_2Os
2170°
2280°
<1·0
Liquid
1280°
970 ± 5°
1030°
78
82
900°
60
920°(?)
γ – U
686°
β – U
620°
92
≥99·5
97
α – U
0 10 20 30 40 50 60 70 80 90 100
At.% U

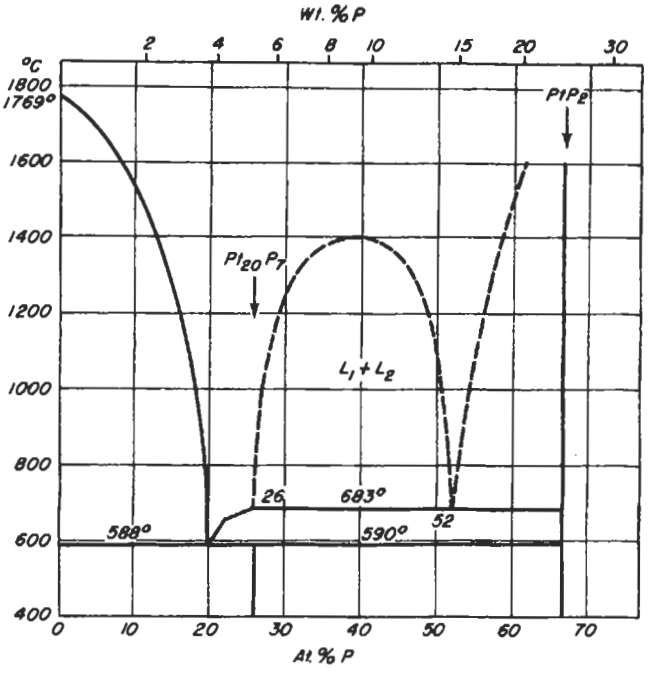
Os–W


°C
3800
3400
3000
2600
2200
1800
1400
1000
Liquid
αW
δ
θ-Os
0 10 20 30 40 50 60 70 80 90 100
At.% Os

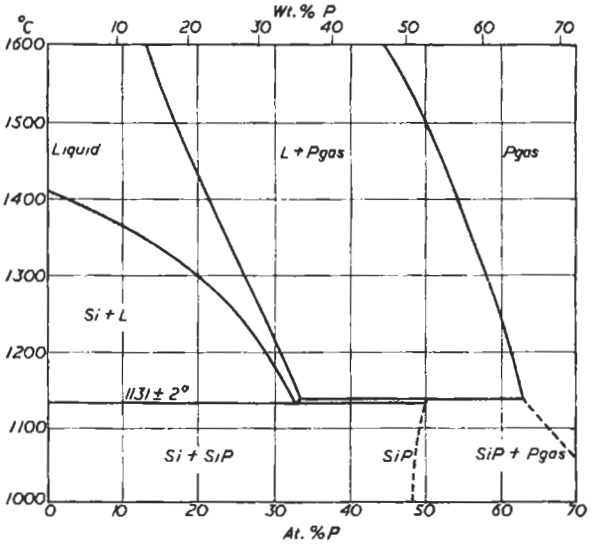
P–Pd


Wt. % P
°C
5 10 15 20 30 40
1600
1553°
1400
1200
1000
800
600
Pd_8P
Pd_7P_3
L
PdP_2
Pd_3P
Pd_6P
Pd_5P_2
~1150°
$Pd_{4.8}P$
814°
852°
799°
792°
778°
771°
0 10 20 30 40 50 60 70
At. % P

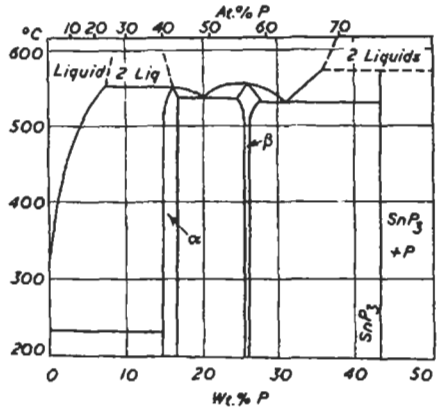
P–Pt


Wt. % P
2
4
6
8
10
15
20
30
°C
1800
1769°
1600
1400
1200
1000
800
600
400
Pt_2P
$Pt_{20}P_7$
$L_1 + L_2$
26
683°
52
588°
590°
0
10
20
30
40
50
60
70
At. % P

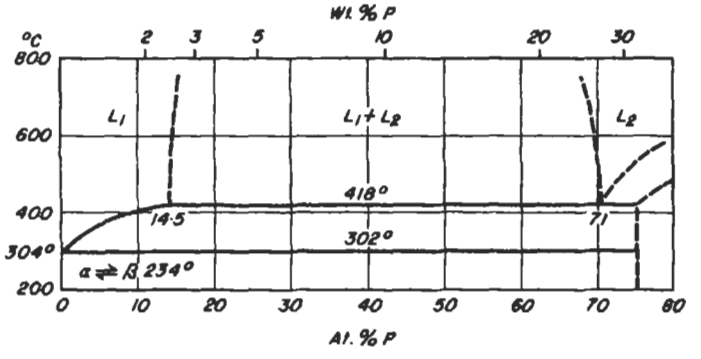
P–Si


°C
Wt. % P
10
20
30
40
50
60
70
1600
1500
1400
1300
1200
1100
1000
Liquid
L + Pgas
Pgas
Si + L
1131 ± 2°
Si + SiP
SiP
SiP + Pgas
0
10
20
30
40
50
60
70
At. % P

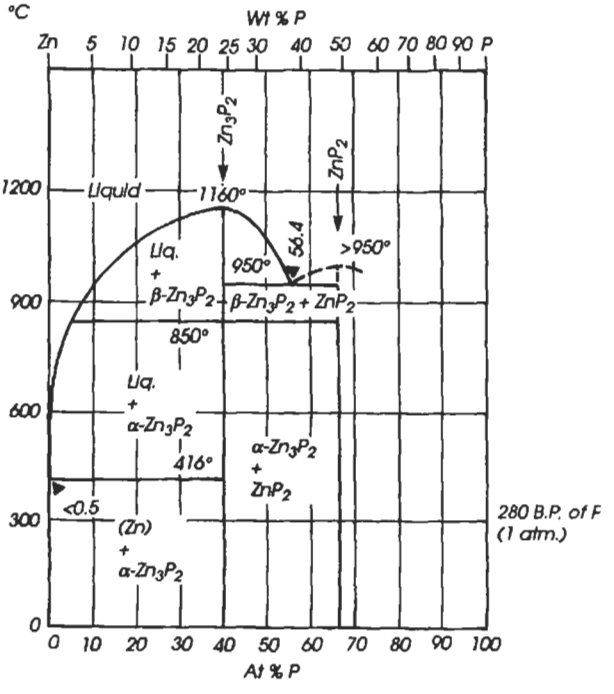
P–Sn


At.% P
°C
10 20 30 40 50 60 70
600
500
400
300
200
Liquid
2 Liq
2 Liquids
β
α
SnP_3 + P
SnP_3
0 10 20 30 40 50
Wt.% P

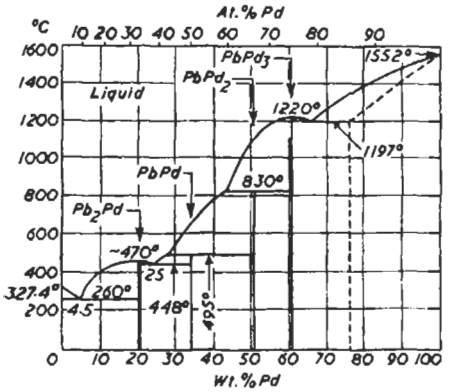
P–Tl


Wt % P
°C
2 3 5 10 20 30
800
600
400
304°
200
L_1
$L_1 + L_2$
L_2
418°
14·5
71
302°
α ⇌ β 234°
0 10 20 30 40 50 60 70 80
At. % P

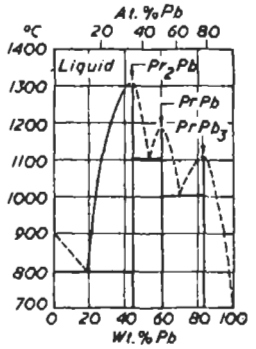
P–Zn


°C
Wt % P
Zn 5 10 15 20 25 30 40 50 60 70 80 90 P
Zn_3P_2
ZnP_2
1200
Liquid
1160°
56.4
>950°
Liq. + β-Zn_3P_2
950°
β-Zn_3P_2 + ZnP_2
900
850°
Liq. + α-Zn_3P_2
600
416°
α-Zn_3P_2 + ZnP_2
<0.5
300
(Zn) + α-Zn_3P_2
280 B.P. of P (1 atm.)
0
0 10 20 30 40 50 60 70 80 90 100
At % P

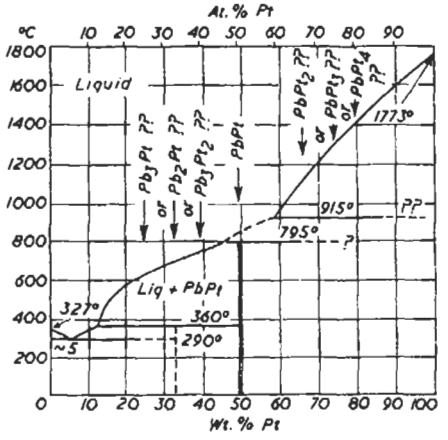
Pb–Pd



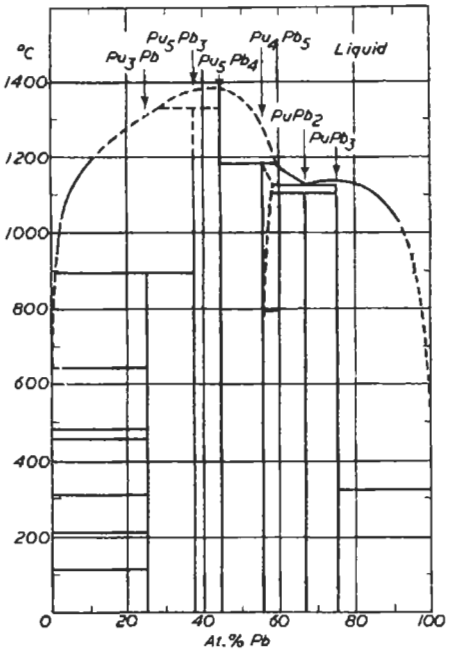
Pb–Pr



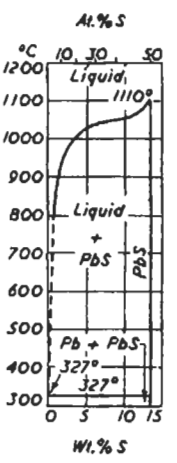
Pb–Pt



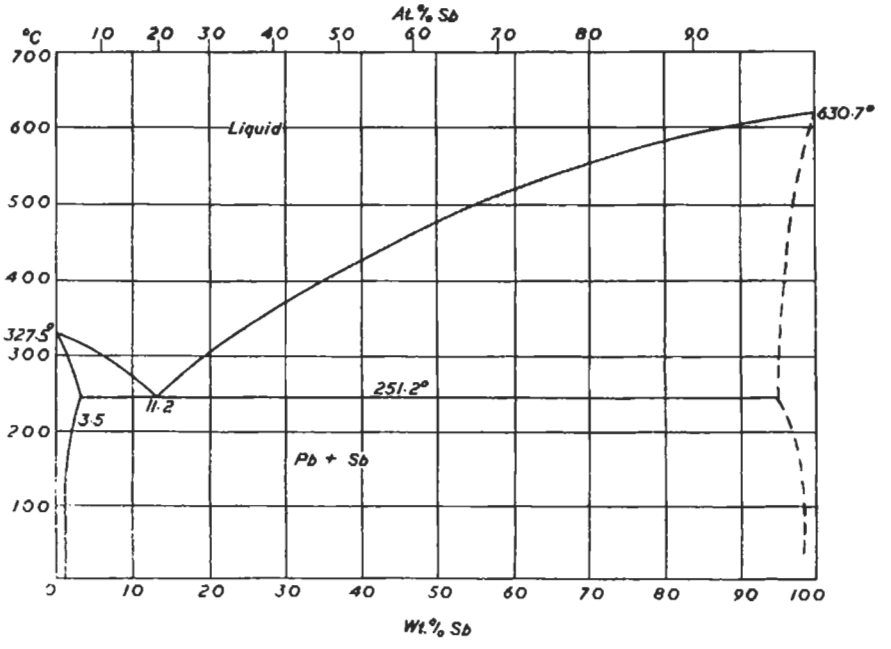
Pb–Pu



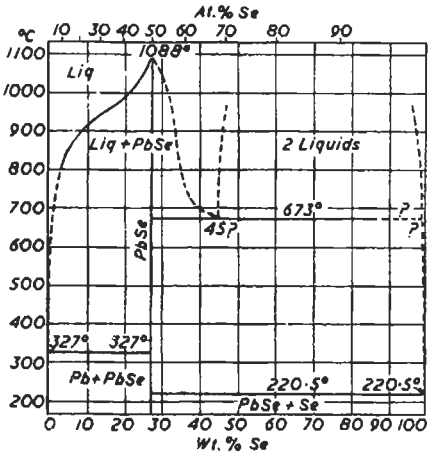
Pb–S



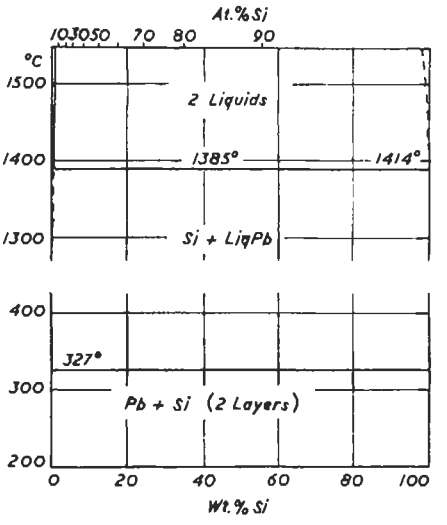
Pb–Sb



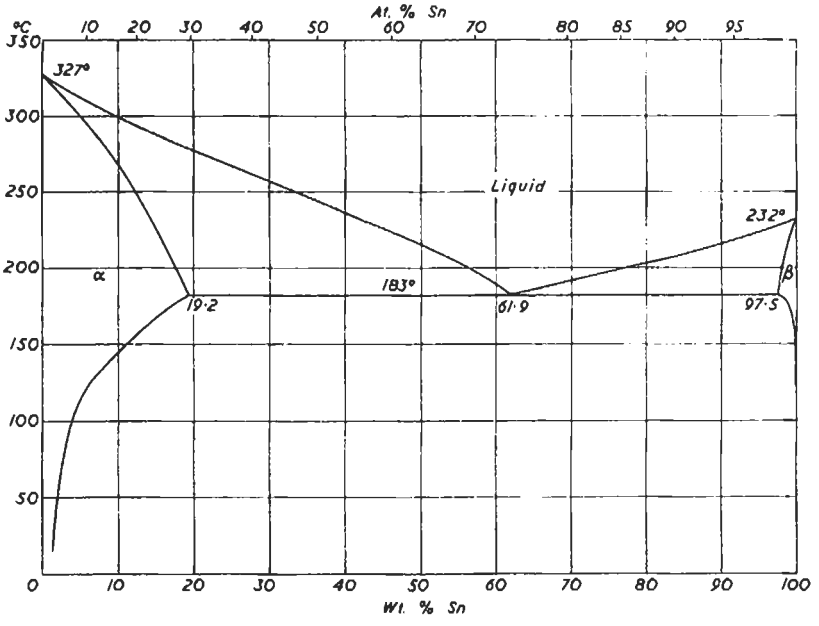
Pb–Se



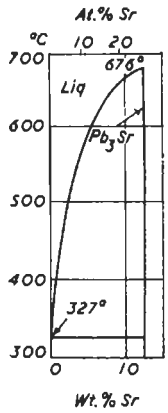
Pb–Si



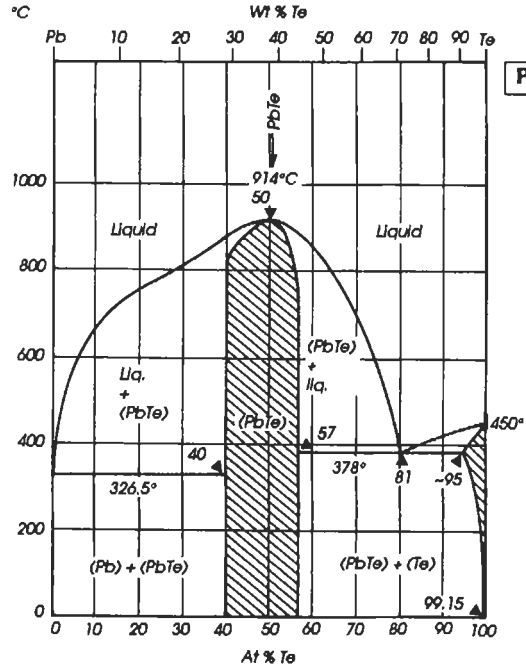
Pb–Sn



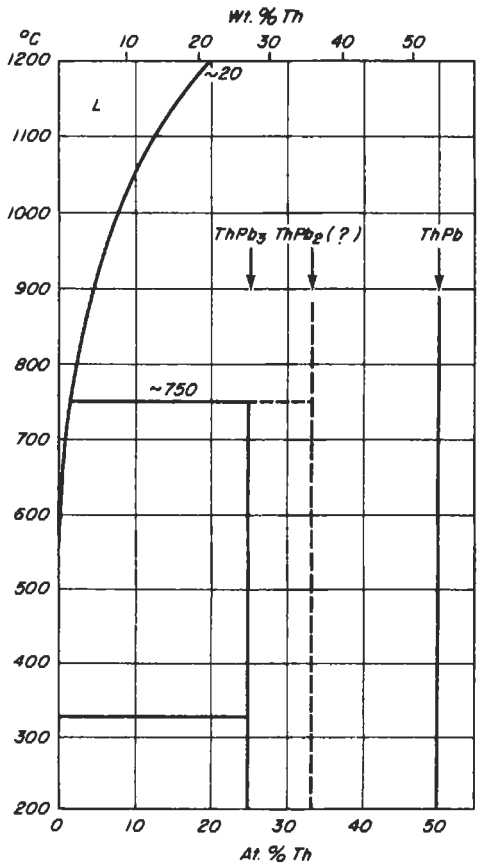
Pb–Sr



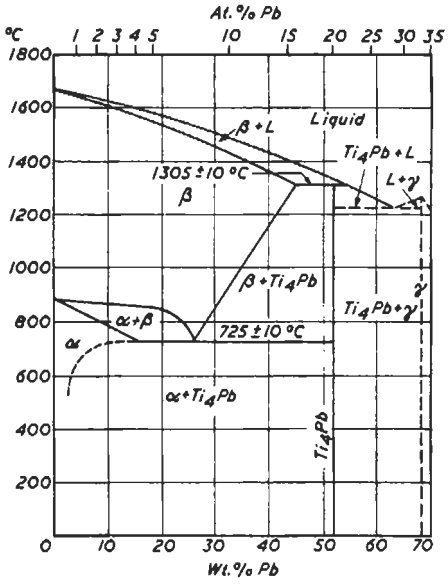
Pb–Te



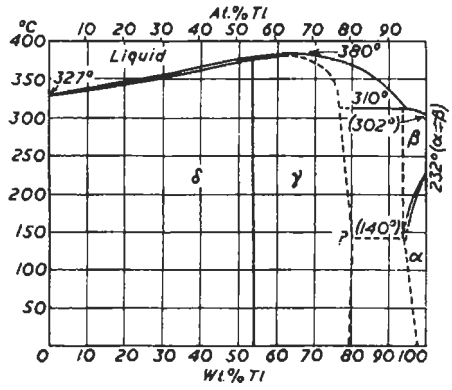
Pb–Th



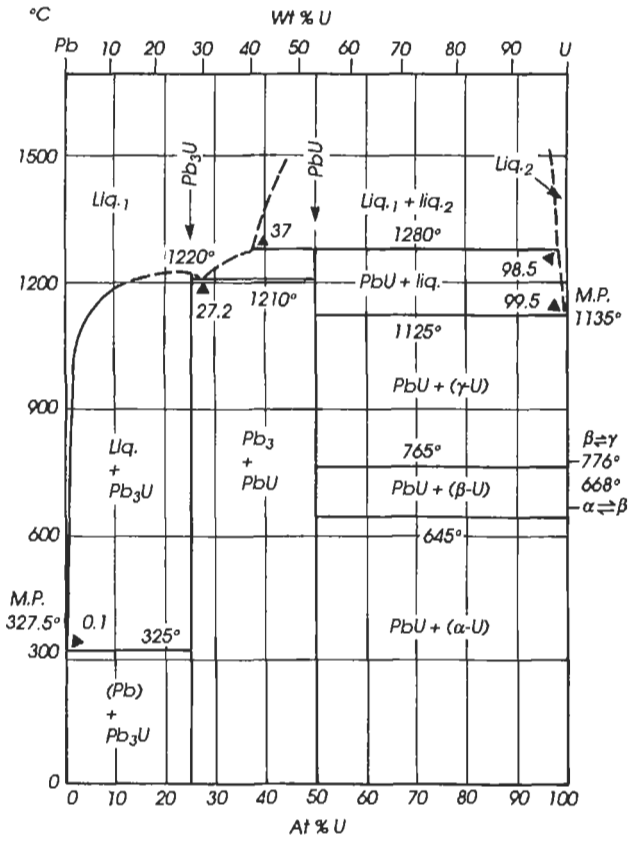
Pb–Ti


At. % Pb
°C
1 2 3 4 5 10 15 20 25 30 35
1800
1600
1400
1200
1000
800
600
400
200
0 10 20 30 40 50 60 70
Wt. % Pb
Liquid
β + L
Ti4Pb + L
L + γ
1305 ± 10 °C
β
β + Ti4Pb
α + β
725 ± 10 °C
α
α + Ti4Pb
Ti4Pb
γ
Ti4Pb + γ

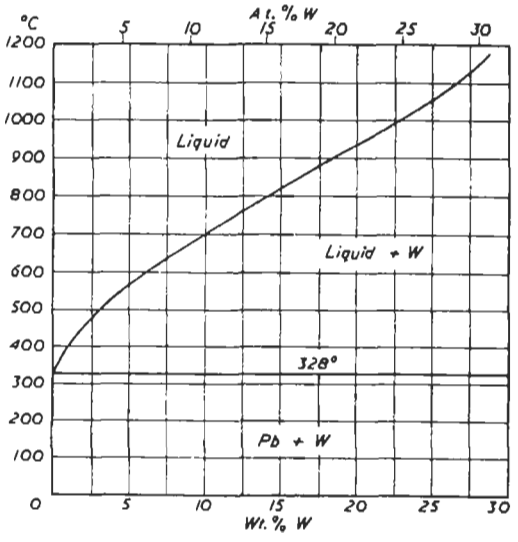
Pb–Tl


At. % Tl
°C
10 20 30 40 50 60 70 80 90
400
350
300
250
200
150
100
50
0 10 20 30 40 50 60 70 80 90 100
Wt. % Tl
Liquid
327°
380°
310°
(302°)
β
232°(α=β)
δ
γ
?
(140°)
α

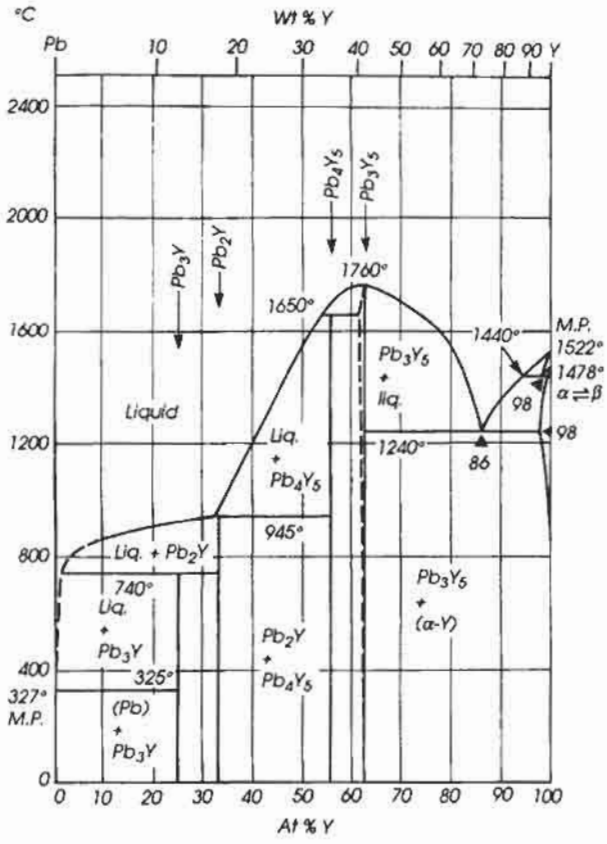
Pb–U


°C
Wt % U
Pb 10 20 30 40 50 60 70 80 90 U
1500
1200
900
600
300
0
Liq.1
Pb3U
PbU
Liq.1 + liq.2
Liq.2
37
1220°
1280°
98.5
PbU + liq.
27.2
1210°
99.5
M.P.
1135°
1125°
PbU + (γ-U)
Liq.
+
Pb3U
Pb3
+
PbU
765°
β⇌γ
776°
668°
α⇌β
PbU + (β-U)
645°
M.P.
327.5°
0.1
325°
PbU + (α-U)
(Pb)
+
Pb3U
0 10 20 30 40 50 60 70 80 90 100
At % U

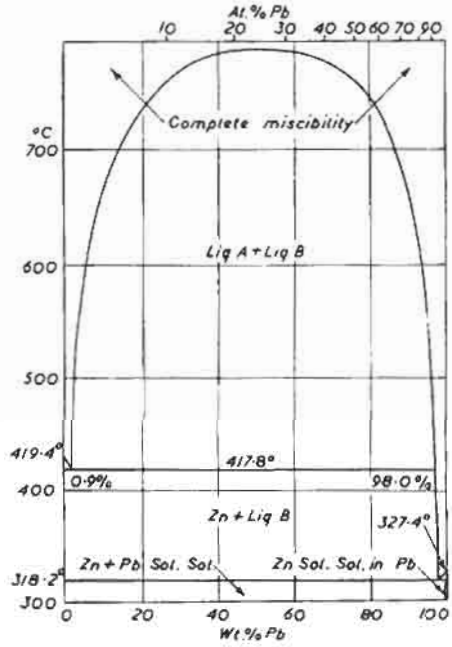
Pb–W


°C
At. % W
5 10 15 20 25 30
1200
1100
1000
900
800
700
600
500
400
300
200
100
0
Liquid
Liquid + W
328°
Pb + W
5 10 15 20 25 30
Wt. % W

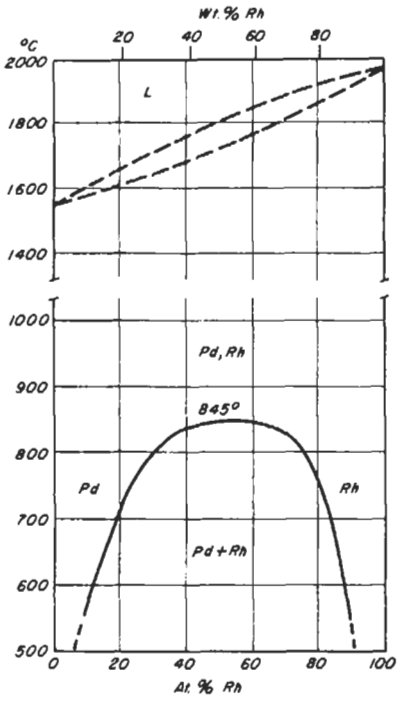
Pb–Y


°C
Wt % Y
Pb
10
20
30
40
50
60
70
80
90
Y
2400
2000
1600
1200
800
400
0
Pb_4Y_5
Pb_3Y_5
Pb_3Y
Pb_2Y
1760°
1650°
1440°
M.P.
1522°
1478°
α ⇌ β
Pb_3Y_5
+
liq.
98
Liquid
Liq.
+
Pb_4Y_5
1240°
86
945°
Liq. + Pb_2Y
740°
Liq.
+
Pb_3Y
Pb_3Y_5
+
(α-Y)
Pb_2Y
+
Pb_4Y_5
325°
327°
M.P.
(Pb)
+
Pb_3Y
0
10
20
30
40
50
60
70
80
90
100
At % Y

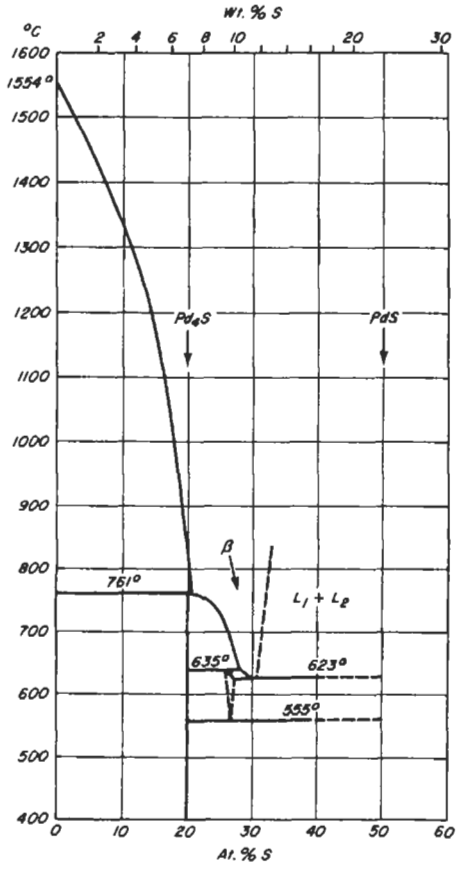
Pb–Zn


At.% Pb
10
20
30
40
50
60
70
90
°C
700
600
500
419·4°
417·8°
400
0·9%
98·0%
327·4°
318·2°
300
Complete miscibility
Liq A + Liq B
Zn + Liq B
Zn + Pb Sol. Sol.
Zn Sol. Sol. in Pb
0
20
40
60
80
100
Wt.% Pb

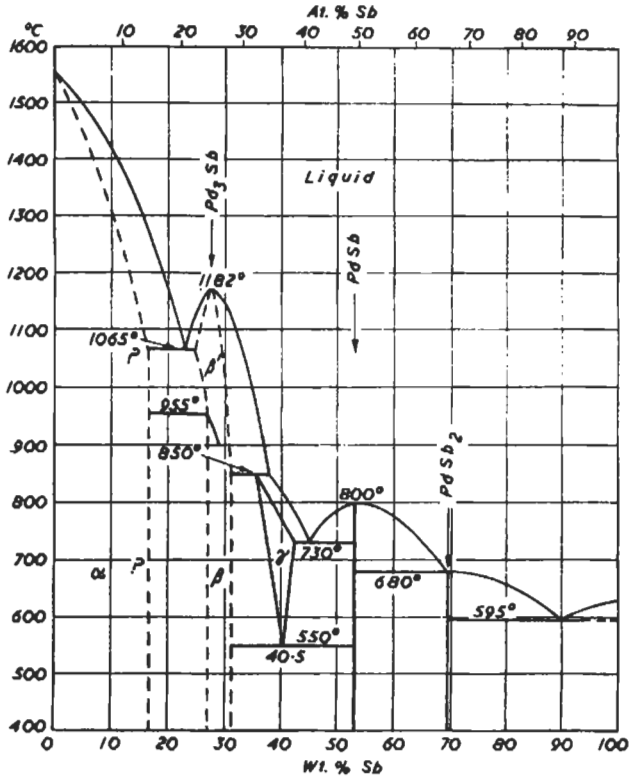
Pd–Rh


Wt. % Rh
°C
20
40
60
80
2000
1800
1600
1400
L
1000
900
800
700
600
500
Pd, Rh
845°
Pd
Rh
Pd + Rh
0
20
40
60
80
100
At. % Rh

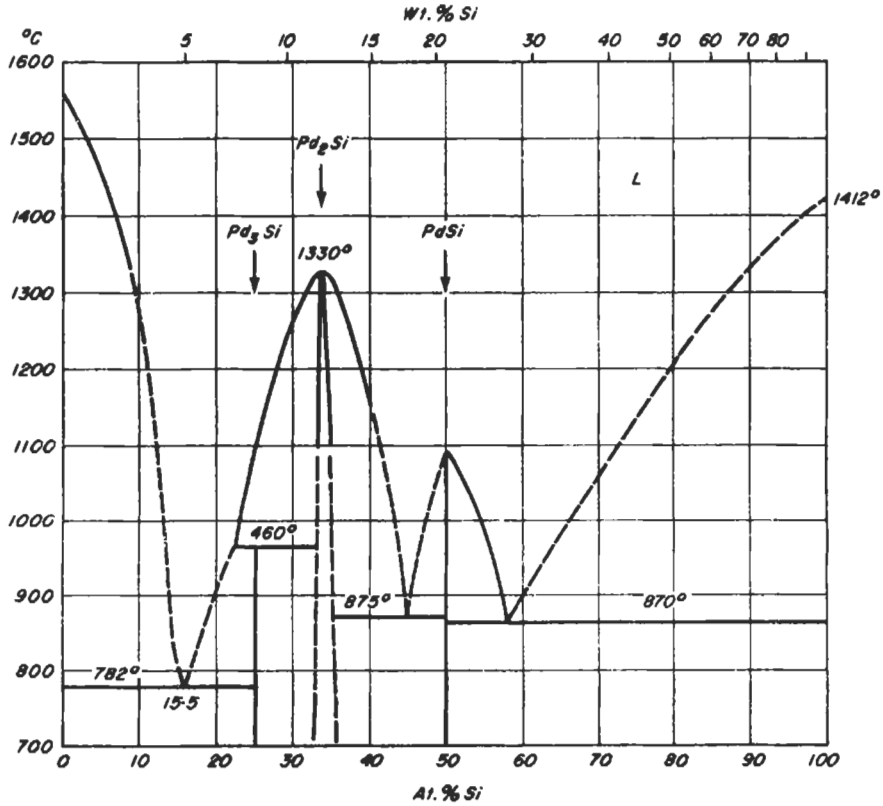
Pd–S


Wt. % S
°C
2
4
6
8
10
20
30
1600
1554°
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
Pd_4S
PdS
β
761°
$L_1 + L_2$
635°
623°
555°
0
10
20
30
40
50
60
At. % S

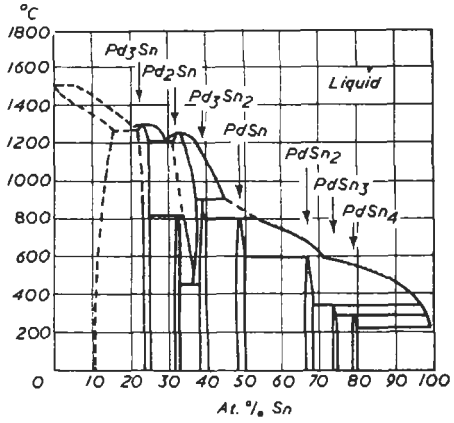
Pd–Sb


°C
At. % Sb
Wt. % Sb
Liquid
Pd_3Sb
PdSb
$PdSb_2$
1182°
1065°
955°
830°
800°
730°
680°
595°
550°
40·5
α
β
γ
P

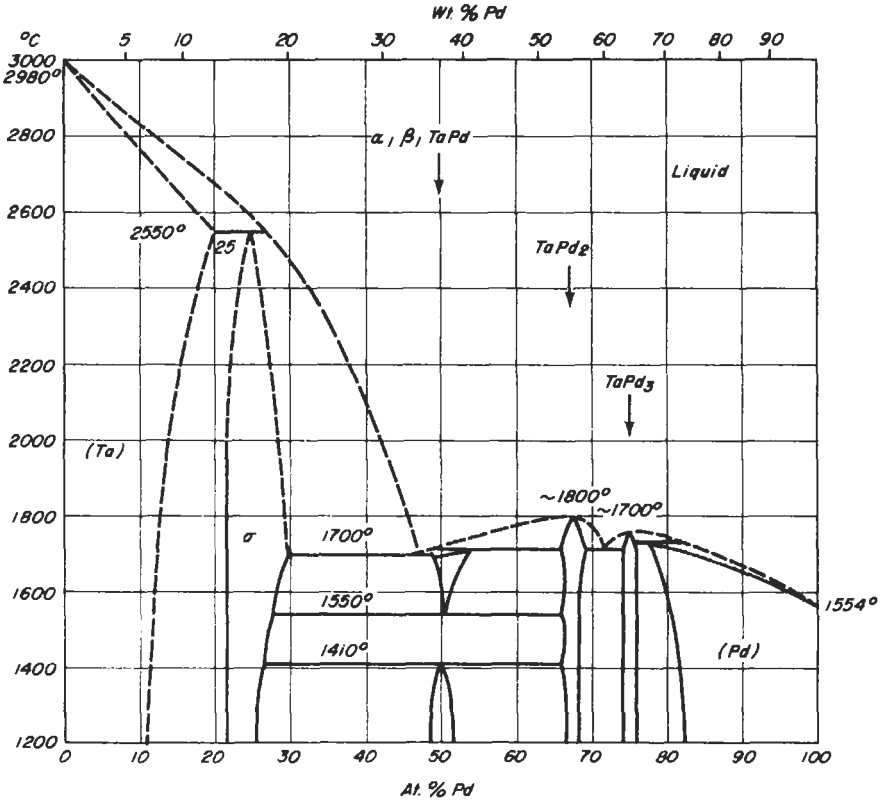
Pd–Si


°C
Wt. % Si
At. % Si
L
Pd_2Si
Pd_3Si
PdSi
1330°
1412°
870°
875°
460°
782°
15·5

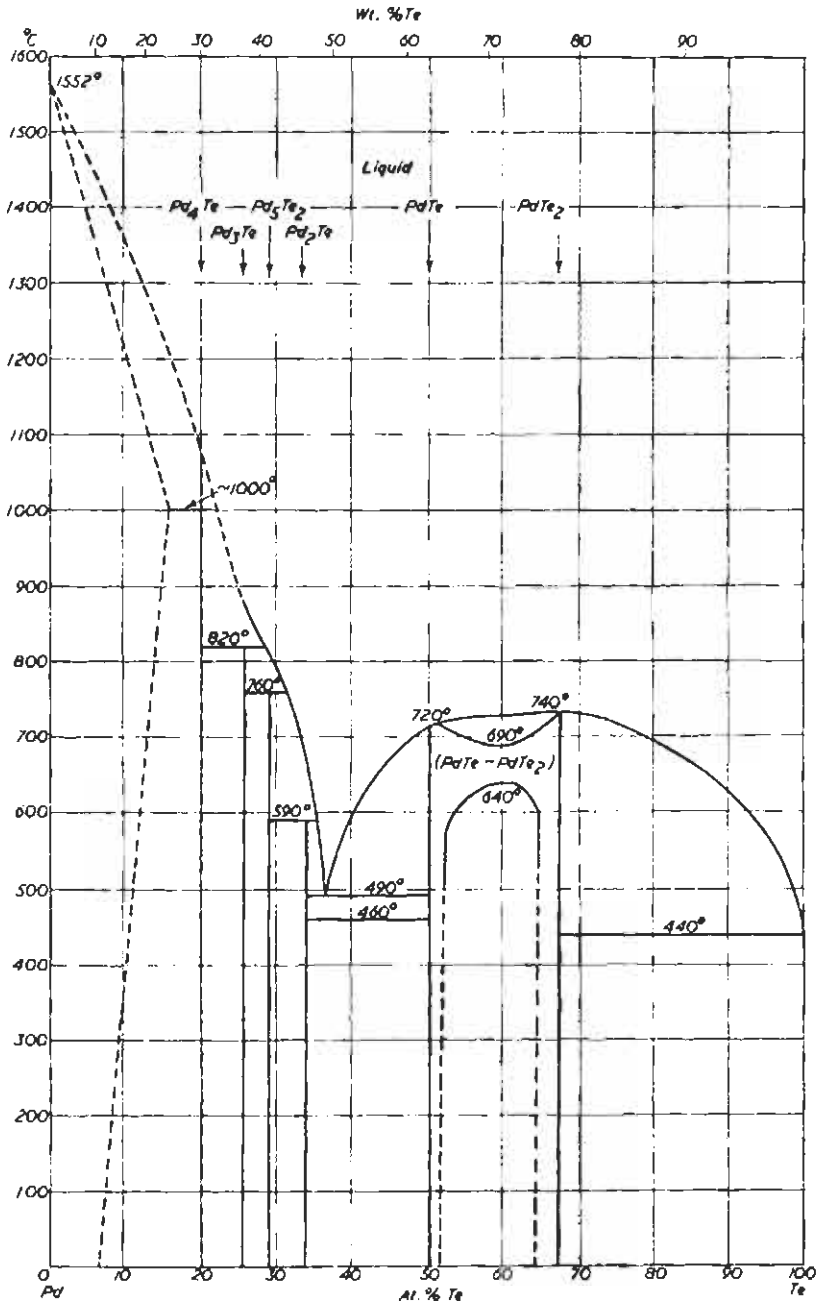
Pd–Sn


°C
1800
1600
1400
1200
1000
800
600
400
200
0
Pd3Sn
Pd2Sn
Pd3Sn2
PdSn
PdSn2
PdSn3
PdSn4
Liquid
10 20 30 40 50 60 70 80 90 100
At. % Sn

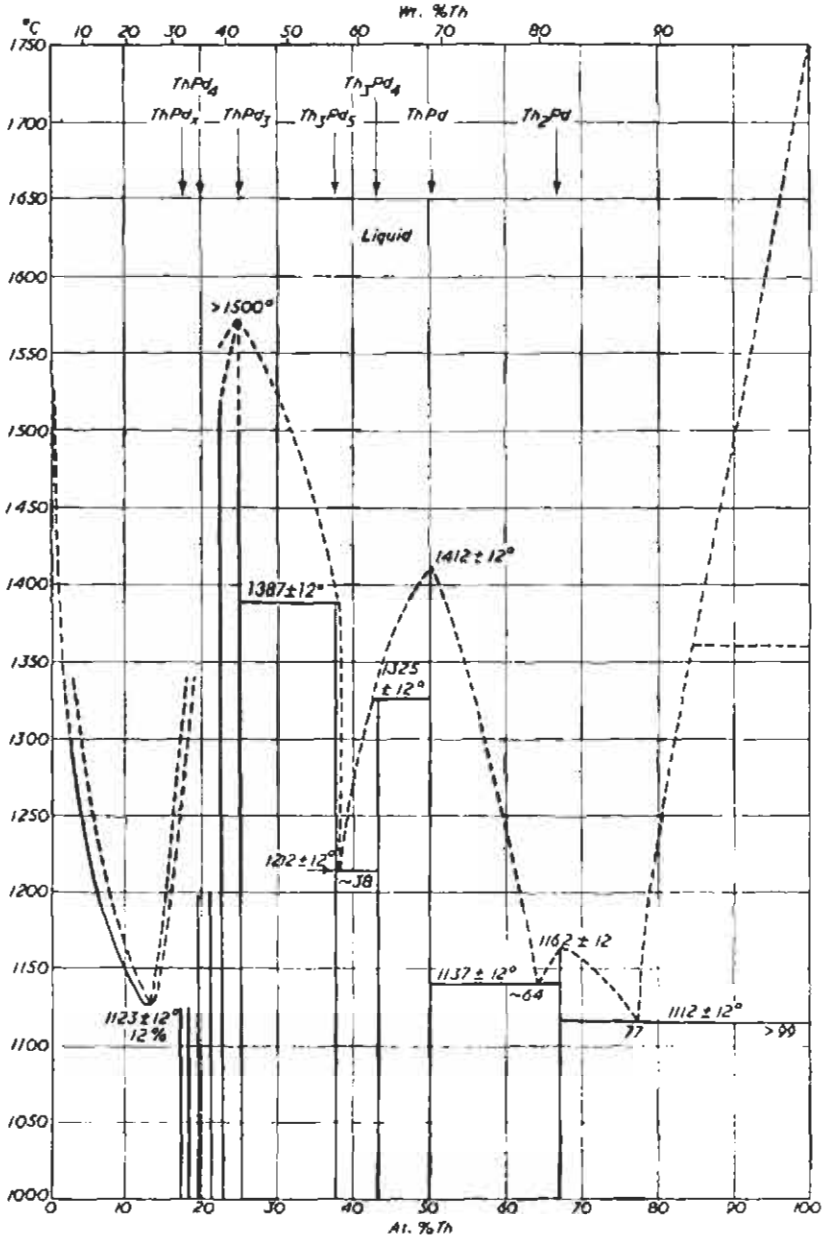
Pd–Ta


Wt. % Pd
°C
5 10 20 30 40 50 60 70 80 90
3000
2980°
2800
2600
2400
2200
2000
1800
1600
1400
1200
α, β, TaPd
Liquid
2550°
25
TaPd2
TaPd3
(Ta)
σ
~1800°
~1700°
1700°
1550°
1410°
1554°
(Pd)
0 10 20 30 40 50 60 70 80 90 100
At. % Pd

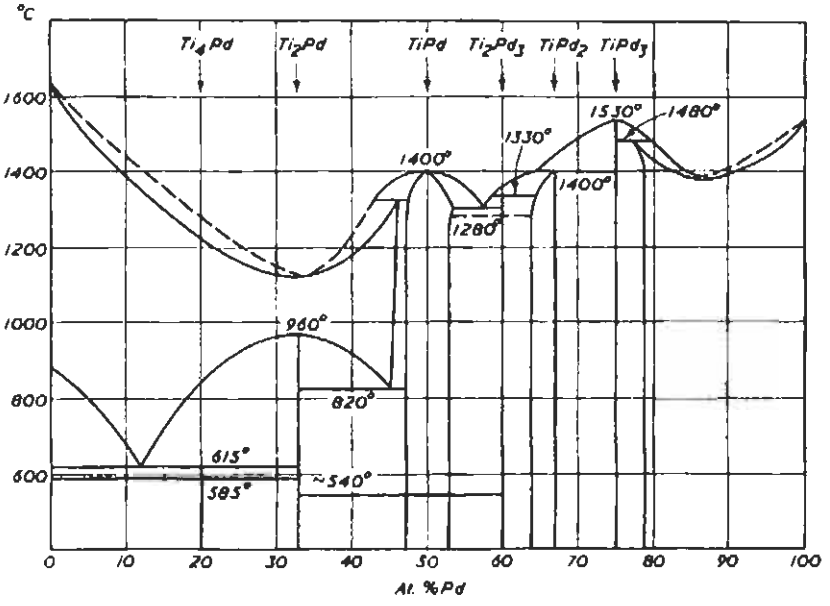
Pd–Te


Wt. %Te
°C
10
20
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
100
1552°
Liquid
Pd_4Te
Pd_5Te_2
$PdTe$
$PdTe_2$
Pd_3Te
Pd_2Te
~1000°
820°
760°
720°
740°
690°
$(PdTe - PdTe_2)$
640°
590°
490°
460°
440°
0
Pd
10
20
30
40
50
60
70
80
90
100
Te
At. % Te

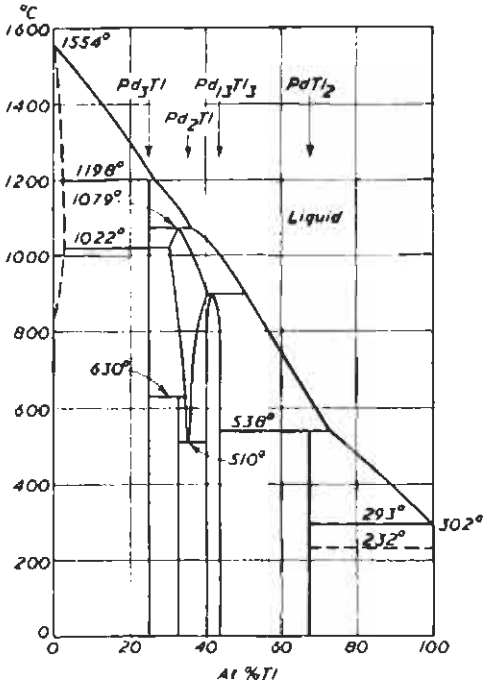
Pd–Th


Wt. %Th
°C
10
20
30
40
50
60
70
80
90
1750
1700
1650
1600
1550
1500
1450
1400
1350
1300
1250
1200
1150
1100
1050
1000
ThPd4
ThPdx
ThPd3
Th3Pd5
Th3Pd4
ThPd
Th2Pd
Liquid
>1500°
1387±12°
1412±12°
1325 ±12°
1202±12°
~38
1162±12
1137±12°
~64
1123±12°
12%
1112±12°
77
>99
0
10
20
30
40
50
60
70
80
90
100
At. %Th

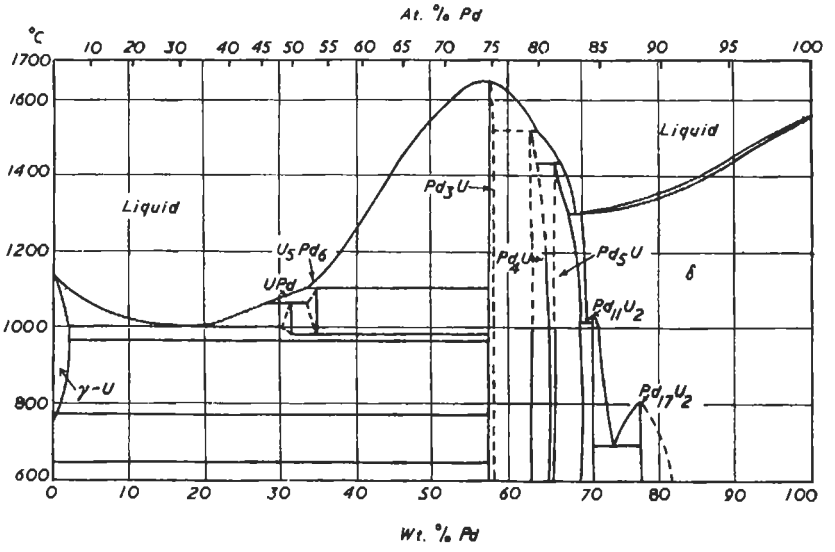
Pd–Ti


°C
Ti4Pd
Ti2Pd
TiPd
Ti2Pd3
TiPd2
TiPd3
1600
1400
1200
1000
800
600
1530°
1480°
1330°
1400°
1400°
1280°
960°
820°
615°
585°
~540°
0
10
20
30
40
50
60
70
80
90
100
At. %Pd

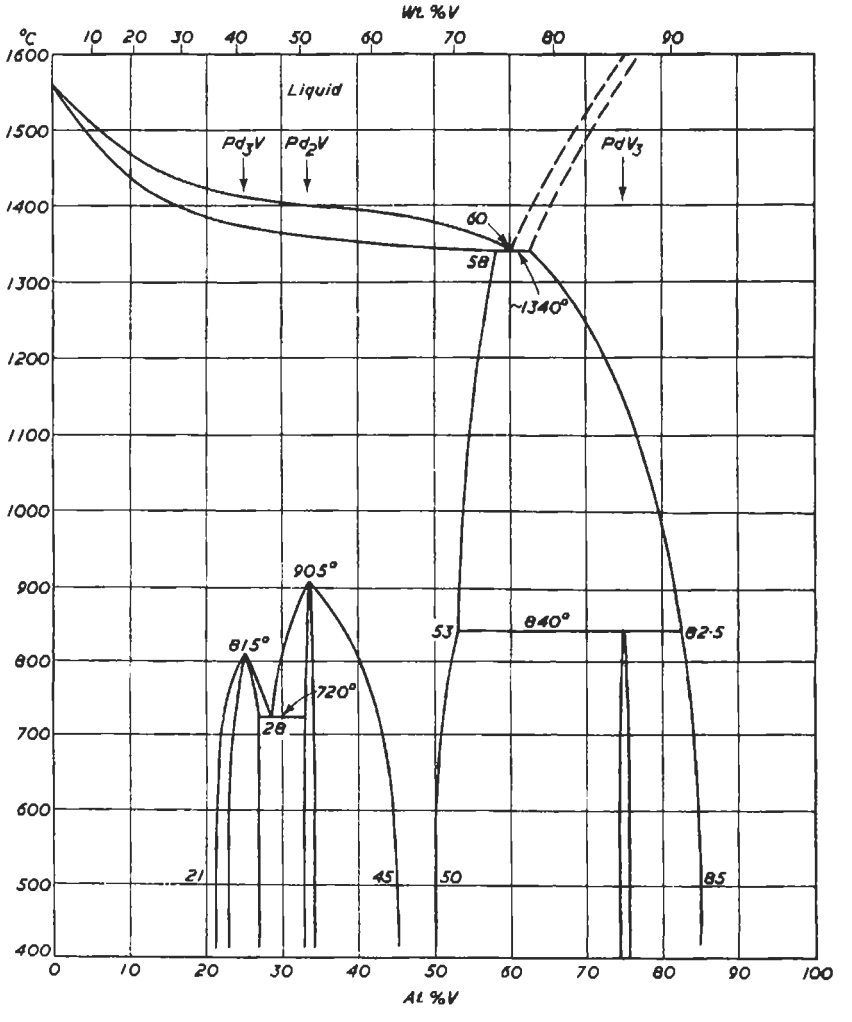
Pd–Tl


°C
1600
1400
1200
1000
800
600
400
200
0
1554°
Pd3Tl
Pd13Tl3
PdTl2
Pd2Tl
1198°
1079°
1022°
Liquid
630°
536°
510°
293°
302°
232°
0
20
40
60
80
100
At %Tl

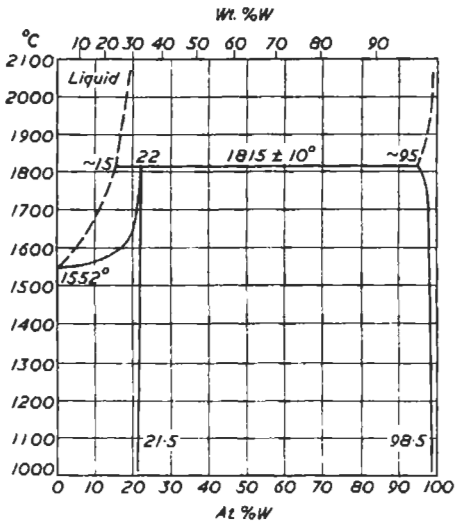
Pd–U


At. % Pd
°C
Liquid
Liquid
Pd_3U
U_5Pd_6
UPd
PdU_4
Pd_5U
$Pd_{11}U_2$
$Pd_{17}U_2$
γ-U
δ
Wt. % Pd

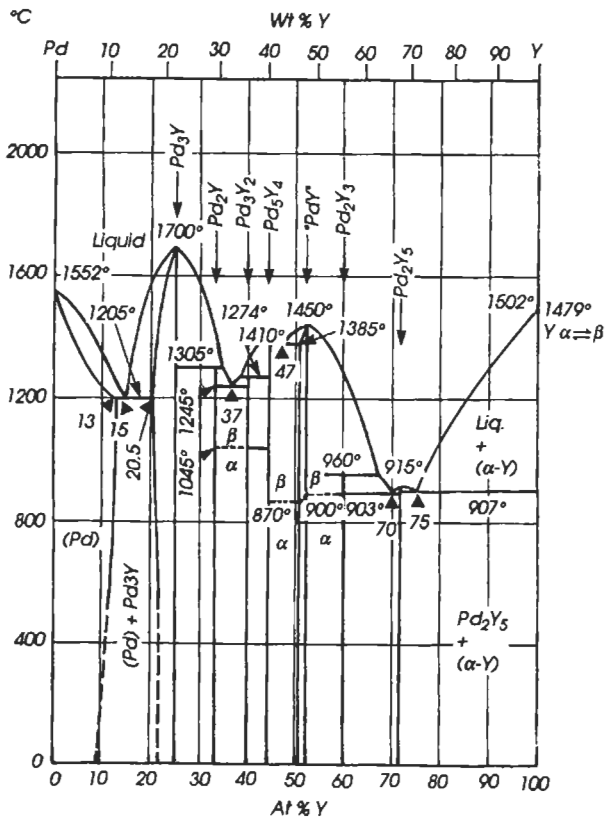
Pd–V


Wt. %V
°C
Liquid
Pd_3V
Pd_2V
PdV_3
60
58
~1340°
905°
815°
720°
28
53
840°
82·5
21
45
50
85
At. %V

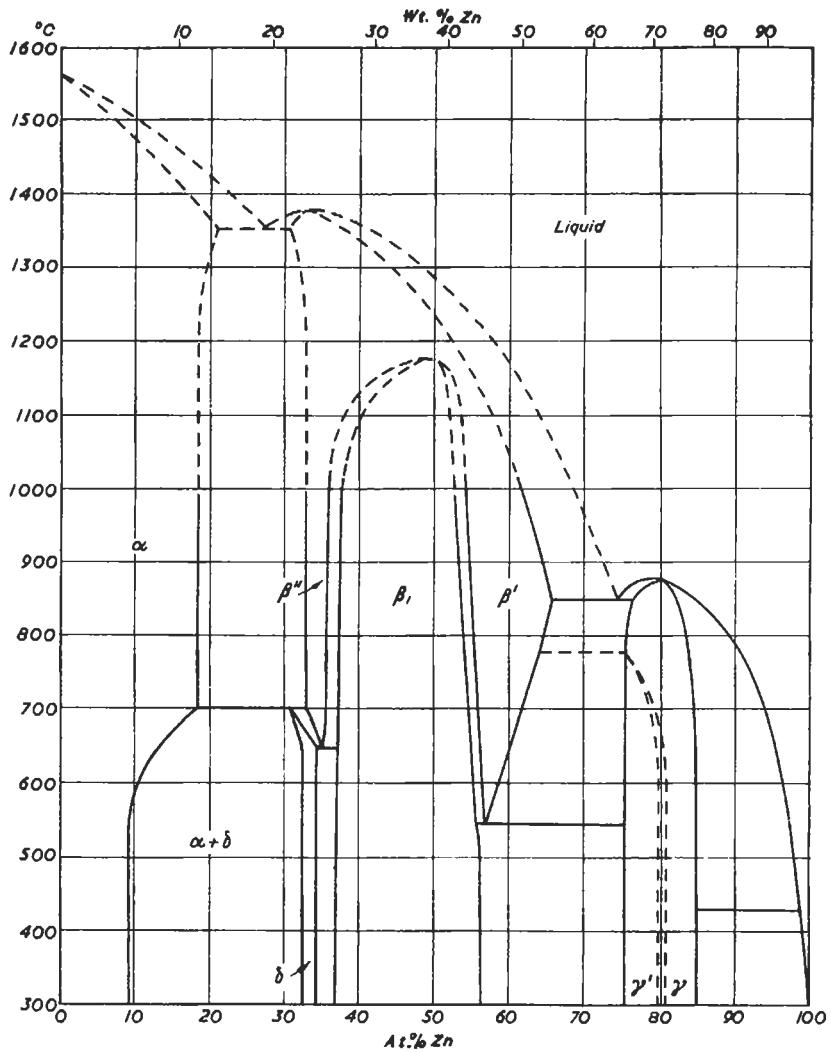
Pd–W


Wt. %W
°C
10 20 30 40 50 60 70 80 90
2100
2000
1900
1800
1700
1600
1500
1400
1300
1200
1100
1000
Liquid
~15
22
1815 ± 10°
~95
1552°
21·5
98·5
0 10 20 30 40 50 60 70 80 90 100
At %W

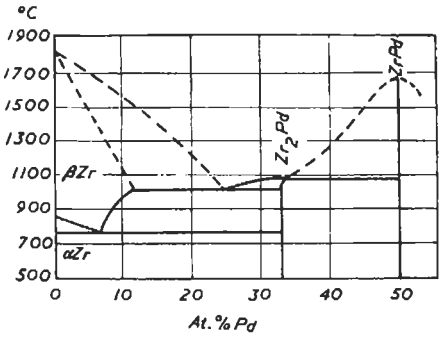
Pd–Y


°C
Wt % Y
Pd 10 20 30 40 50 60 70 80 90 Y
2000
1600
1200
800
400
0
Liquid
1552°
1700°
Pd3Y
Pd2Y
Pd3Y2
Pd5Y4
"PdY"
Pd2Y3
Pd2Y5
1205°
1274°
1450°
1410°
1385°
1305°
1245°
1045°
1502°
1479°
Y α⇌β
13
15
20.5
37
47
β
α
960°
915°
870°
900°
903°
907°
70
75
Liq.
+
(α-Y)
(Pd)
(Pd) + Pd3Y
Pd2Y5
+
(α-Y)
0 10 20 30 40 50 60 70 80 90 100
At % Y

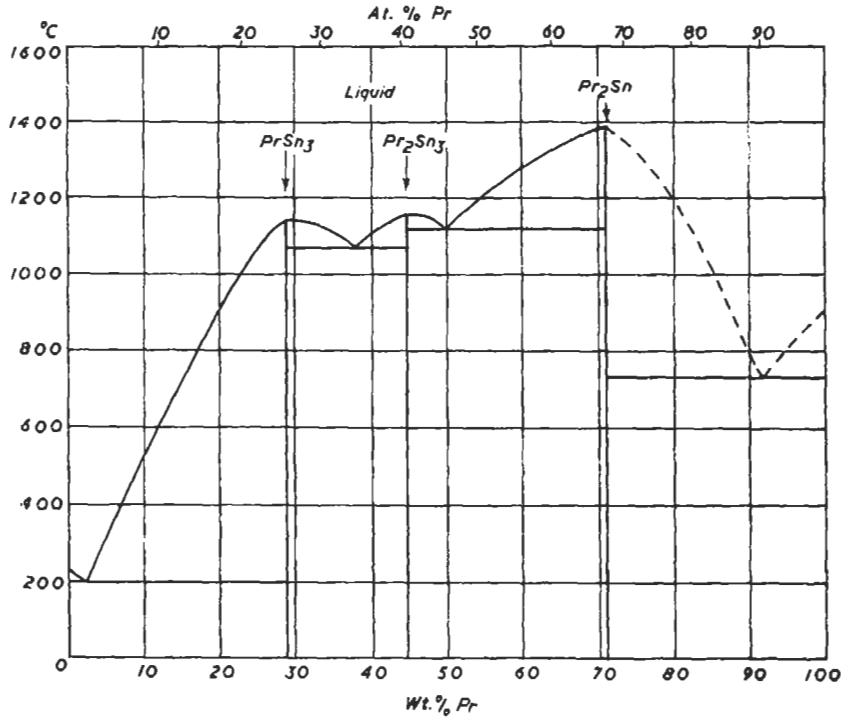
Pd–Zn


°C
Wt. % Zn
10
20
30
40
50
60
70
80
90
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
Liquid
α
β″
β₁
β′
α + δ
δ
γ′
γ
0
10
20
30
40
50
60
70
80
90
100
At.% Zn

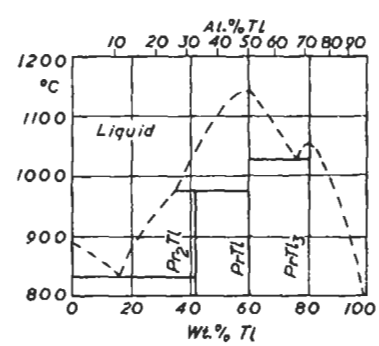
Pd–Zr


°C
1900
1700
1500
1300
1100
900
700
500
βZr
αZr
Zr₂Pd
PdZr
0
10
20
30
40
50
At.% Pd

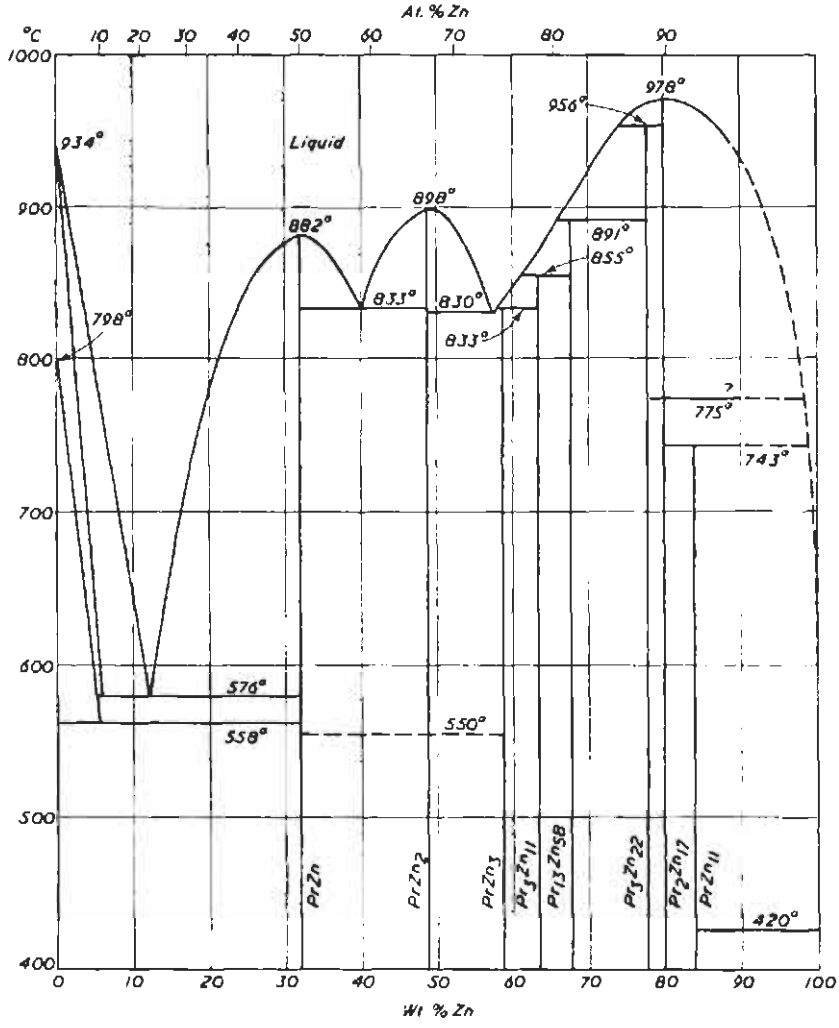
Pr–Sn


At. % Pr
°C
10 20 30 40 50 60 70 80 90
1600
1400
1200
1000
800
600
400
200
0
Liquid
Pr_2Sn
$PrSn_3$
Pr_2Sn_3
10 20 30 40 50 60 70 80 90 100
Wt. % Pr

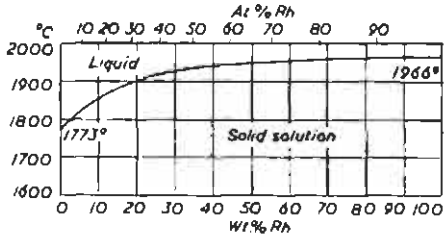
Pr–Tl


At. % Tl
10 20 30 40 50 60 70 80 90
1200
°C
1100
1000
900
800
Liquid
Pr_2Tl
PrTl
$PrTl_3$
0 20 40 60 80 100
Wt. % Tl

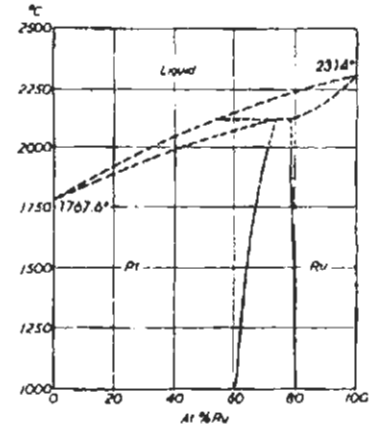
Pr–Zn


At. % Zn
°C
10 20 30 40 50 60 70 80 90
1000
900
800
700
600
500
400
934°
Liquid
882°
898°
956°
978°
891°
855°
833°
830°
833°
798°
775°
743°
576°
558°
550°
PrZn
PrZn2
PrZn3
Pr3Zn11
Pr13Zn58
Pr3Zn22
Pr2Zn17
PrZn11
420°
0 10 20 30 40 50 60 70 80 90 100
Wt % Zn

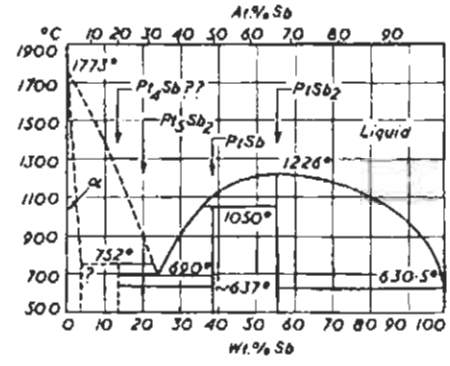
Pt–Rh


At % Rh
°C
10 20 30 40 50 60 70 80 90
2000
1900
1800
1700
1600
Liquid
1966°
1773°
Solid solution
0 10 20 30 40 50 60 70 80 90 100
Wt % Rh

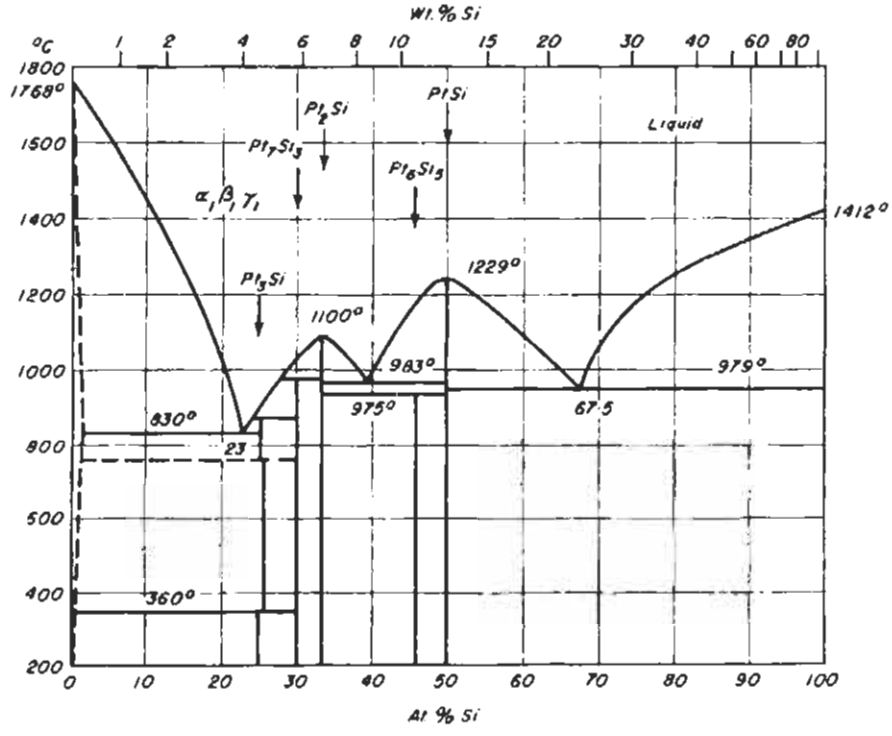
Pt–Ru



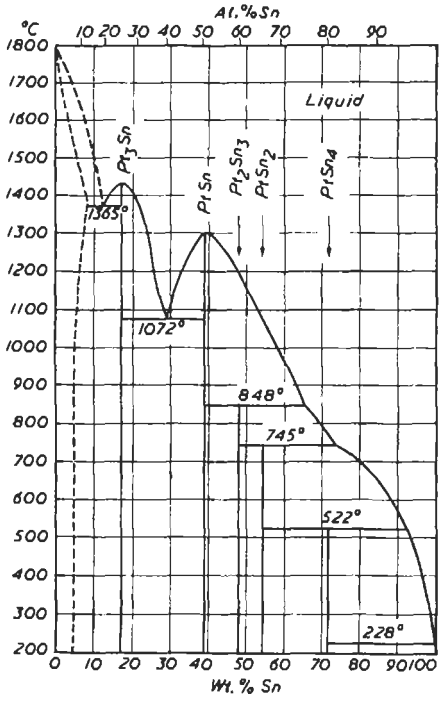
Pt–Sb



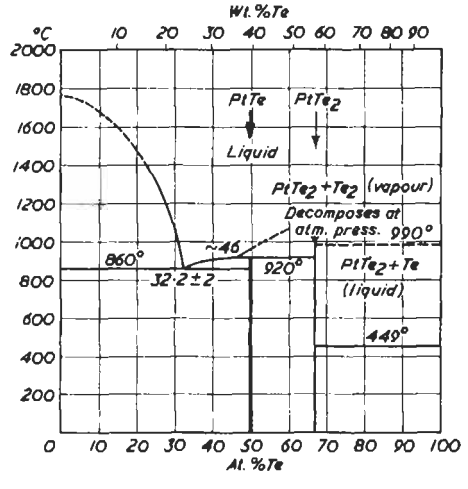
Pt–Si



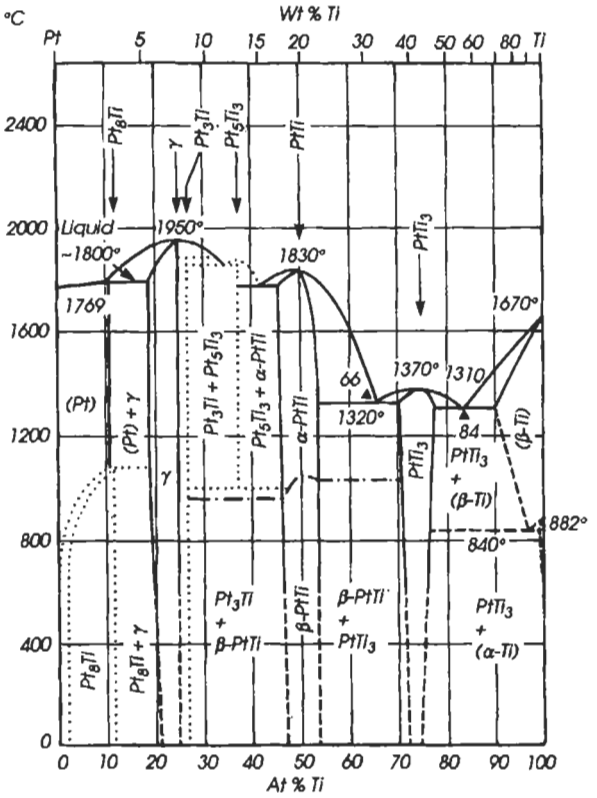
Pt–Sn


At.%Sn
°C
10 20 30 40 50 60 70 80 90
1800
1700
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
300
200
Liquid
Pt3Sn
PtSn
Pt2Sn3
PtSn2
PtSn4
1385°
1072°
848°
745°
522°
228°
0 10 20 30 40 50 60 70 80 90100
Wt. % Sn

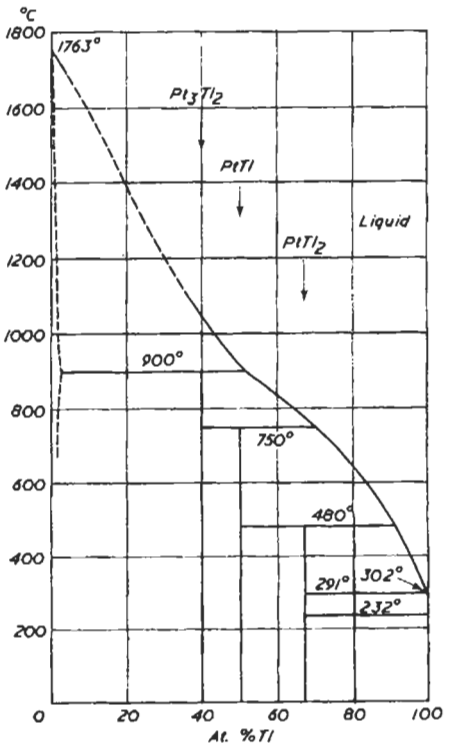
Pt–Te


Wt.%Te
°C
10 20 30 40 50 60 70 80 90
2000
1800
1600
1400
1200
1000
800
600
400
200
PtTe
PtTe2
Liquid
PtTe2+Te2 (vapour)
Decomposes at
atm. press. 990°
~46
860°
32·2±2
920°
PtTe2+Te
(liquid)
449°
0 10 20 30 40 50 60 70 80 90 100
At. %Te

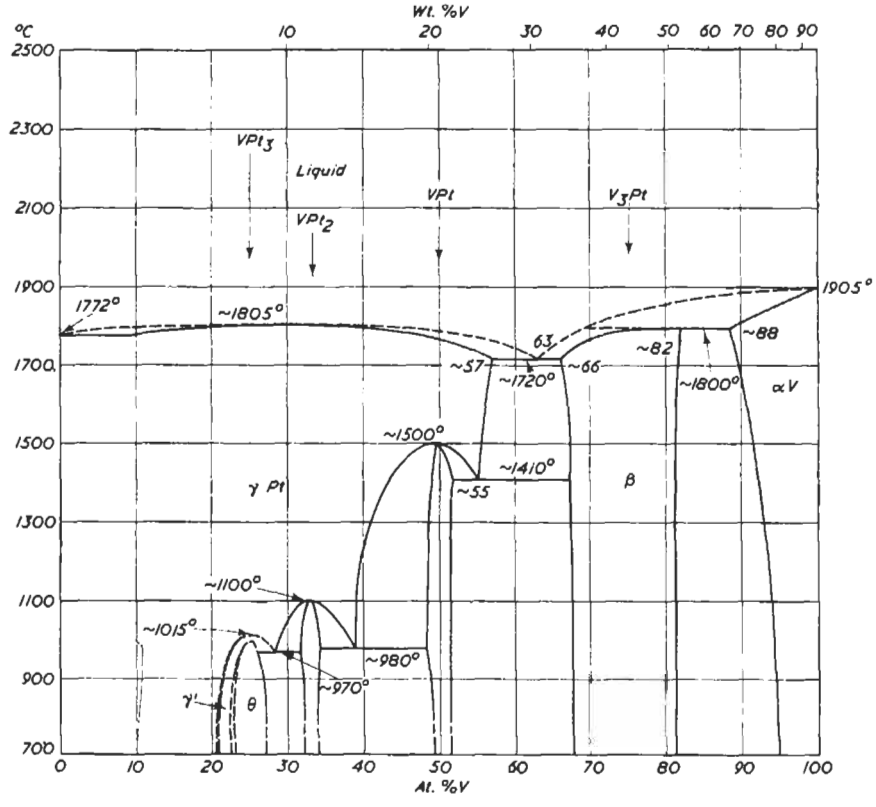
Pt–Ti


°C
Wt % Ti
Pt
5
10
15
20
30
40
50
60
80
Ti
2400
2000
1600
1200
800
400
0
Liquid
~1800°
1950°
1830°
1769
1670°
1370°
1310
66
1320°
84
882°
840°
(Pt)
(Pt) + γ
γ
Pt3Ti + Pt5Ti3
Pt5Ti3 + α-PtTi
α-PtTi
β-PtTi
PtTi3
PtTi3 + (β-Ti)
(β-Ti)
Pt3Ti + β-PtTi
β-PtTi + PtTi3
PtTi3 + (α-Ti)
Pt8Ti
Pt8Ti + γ
0 10 20 30 40 50 60 70 80 90 100
At % Ti

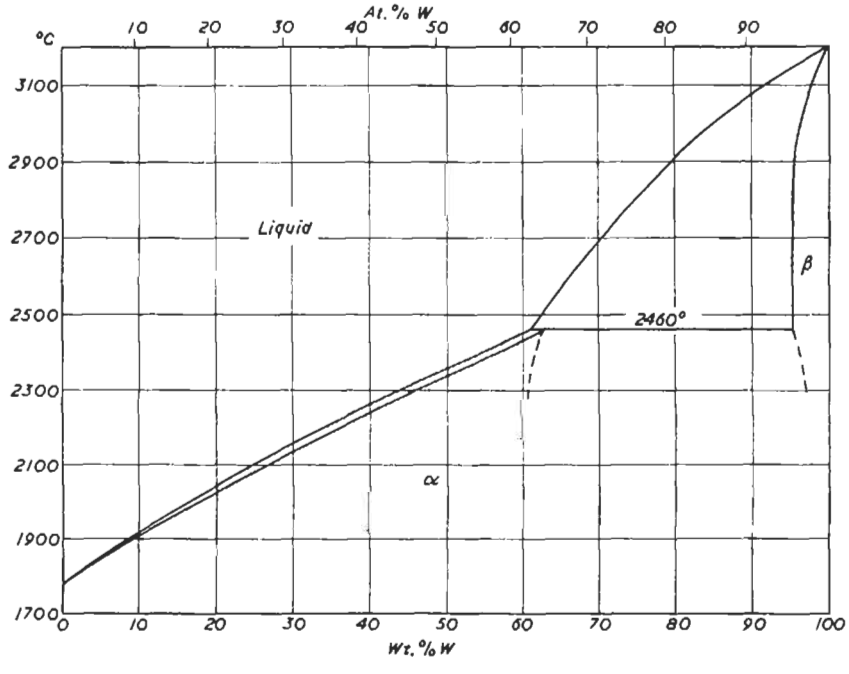
Pt–Tl


°C
1800
1600
1400
1200
1000
800
600
400
200
0
1763°
Pt3Tl2
PtTl
PtTl2
Liquid
900°
750°
480°
291°
302°
232°
0 20 40 60 80 100
At. % Tl

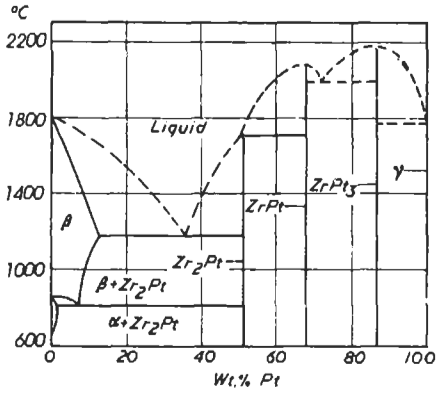
Pt–V


Wt. %V
°C
10
20
30
40
50
60
70
80
90
2500
2300
2100
1900
1700
1500
1300
1100
900
700
VPt3
Liquid
VPt
V3Pt
VPt2
1772°
~1805°
1905°
63
~57
~1720°
~66
~82
~88
~1800°
αV
~1500°
~1410°
γ Pt
~55
β
~1100°
~1015°
~980°
~970°
γ'
θ
0
10
20
30
40
50
60
70
80
90
100
At. %V

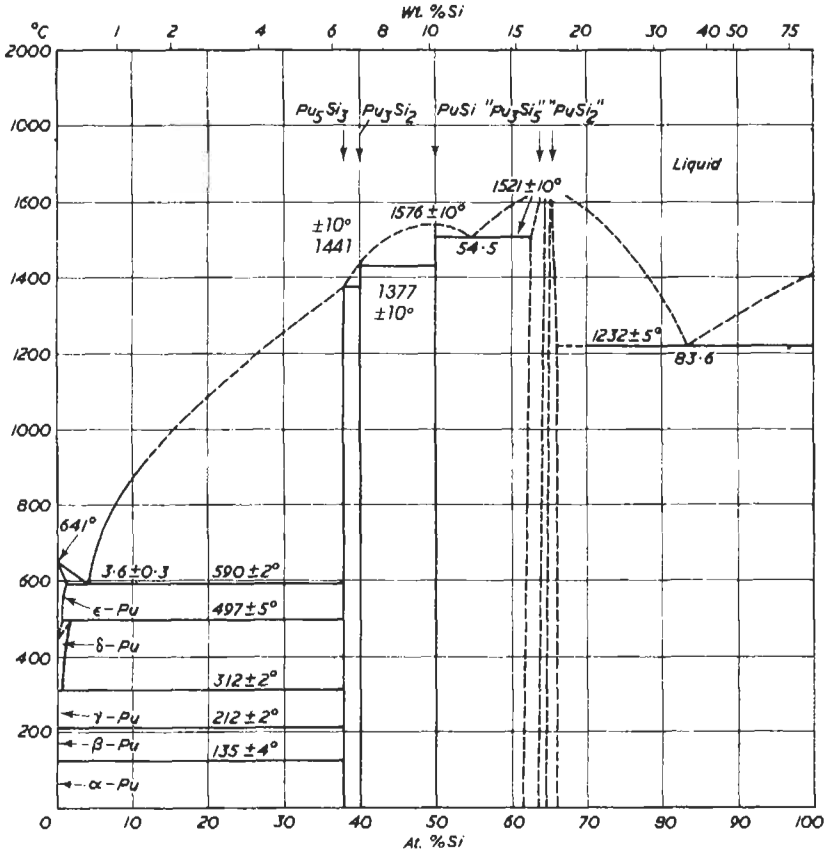
Pt–W


At. % W
°C
10
20
30
40
50
60
70
80
90
3100
2900
2700
2500
2300
2100
1900
1700
Liquid
β
2460°
α
0
10
20
30
40
50
60
70
80
90
100
Wt. % W

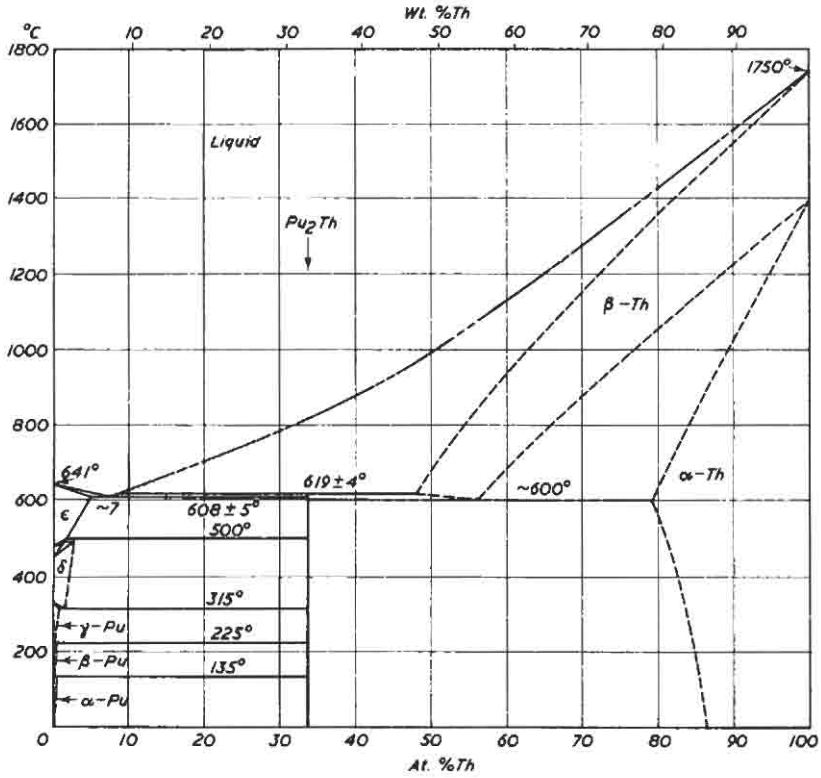
Pt–Zr


°C
2200
1800
1400
1000
600
Liquid
β
ZrPt
ZrPt3
γ
Zr2Pt
β+Zr2Pt
α+Zr2Pt
0
20
40
60
80
100
Wt.% Pt

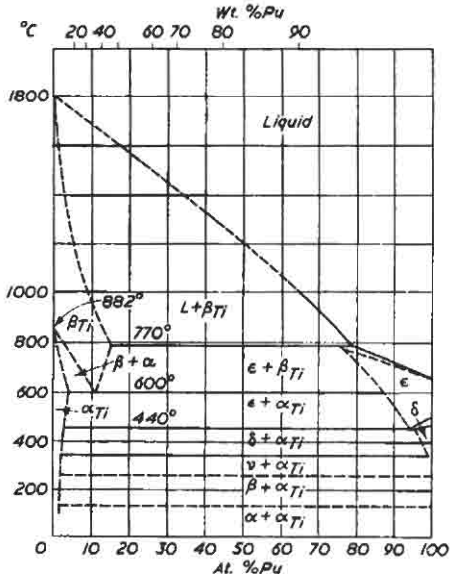
Pu–Si


Wt. %Si
°C
1
2
4
6
8
10
15
20
30
40
50
75
2000
1000
1600
1400
1200
1000
800
600
400
200
0
Pu5Si3
Pu3Si2
PuSi
"Pu3Si5"
"PuSi2"
Liquid
1521±10°
1576±10°
±10°
1441
54·5
1377
±10°
1232±5°
83·6
641°
3·6±0·3
590±2°
ε-Pu
497±5°
δ-Pu
312±2°
γ-Pu
212±2°
β-Pu
135±4°
α-Pu
10
20
30
40
50
60
70
80
90
100
At. %Si

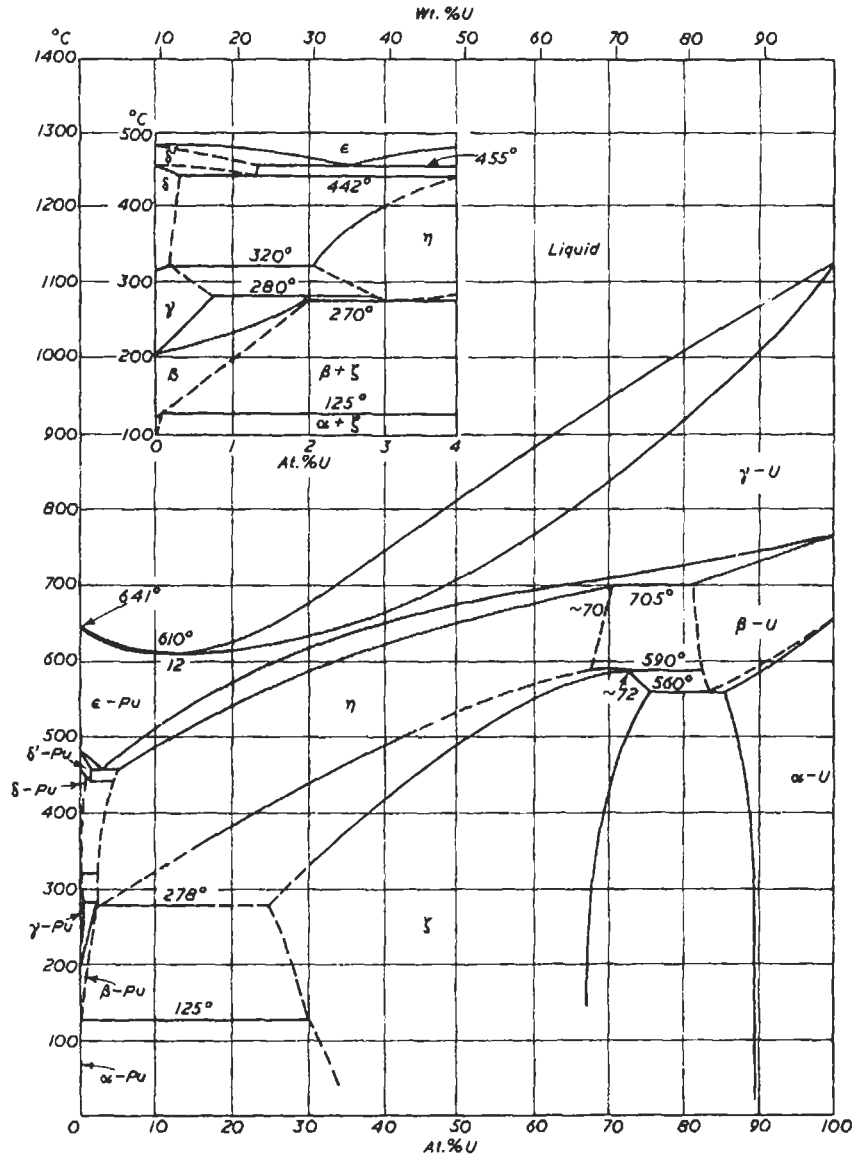
Pu–Th


Wt. %Th
°C
10 20 30 40 50 60 70 80 90
1800
1600
1400
1200
1000
800
600
400
200
0
Liquid
Pu_2Th
β–Th
α–Th
1750°
641°
619 ± 4°
~600°
~7
608 ± 5°
500°
315°
225°
135°
ε
δ
γ–Pu
β–Pu
α–Pu
10 20 30 40 50 60 70 80 90 100
At. %Th

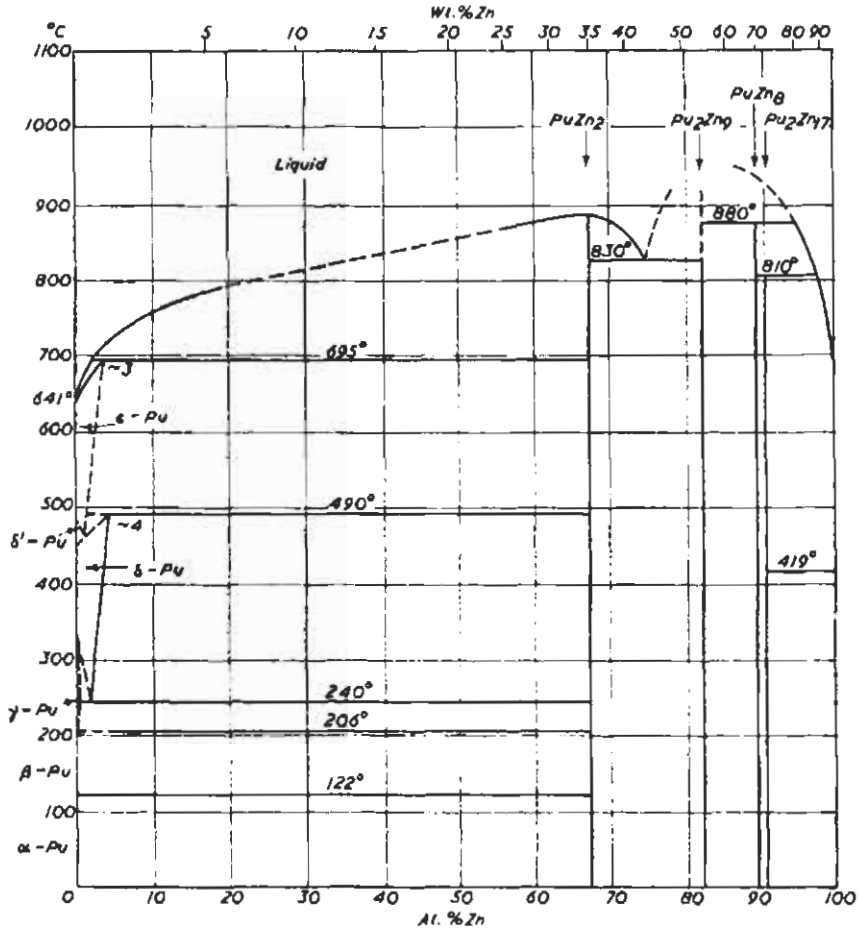
Pu–Ti


Wt. %Pu
°C
20 40 60 70 80 90
1800
1000
800
600
400
200
0
Liquid
882°
$L+\beta_{Ti}$
β_{Ti}
770°
$\beta+\alpha$
600°
α_{Ti}
440°
$\epsilon+\beta_{Ti}$
$\epsilon+\alpha_{Ti}$
$\delta+\alpha_{Ti}$
$\gamma+\alpha_{Ti}$
$\beta+\alpha_{Ti}$
$\alpha+\alpha_{Ti}$
ε
δ
10 20 30 40 50 60 70 80 90 100
At. %Pu

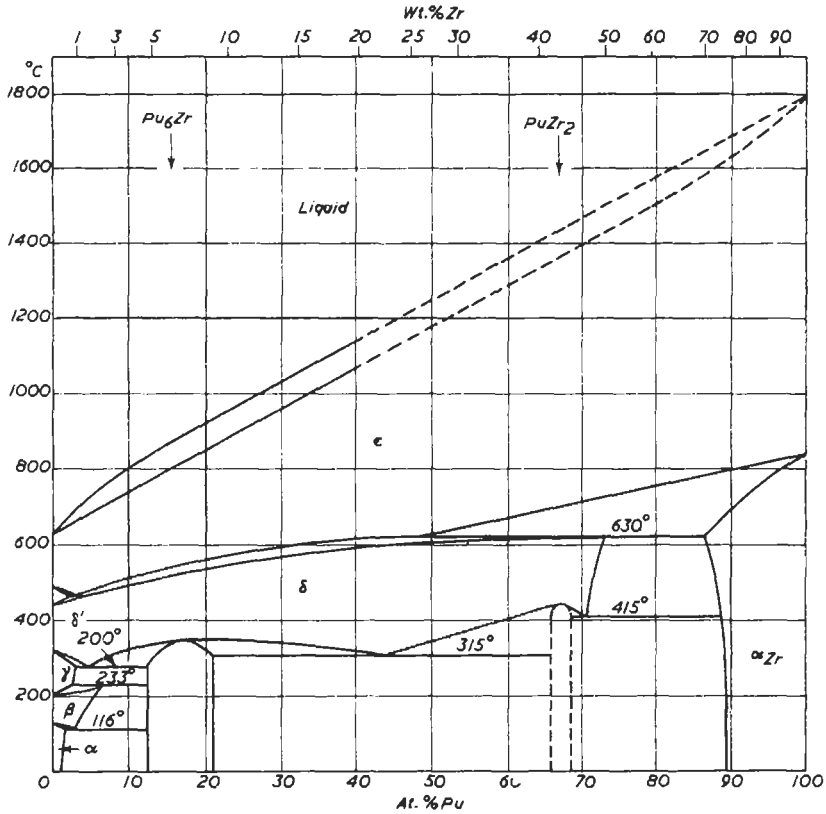
Pu–U


Wt. %U
°C
At.%U
Liquid
ε
δ
δ'
β
γ
η
ζ
α
β+ζ
α+ζ
γ-U
β-U
α-U
ε-Pu
δ'-Pu
δ-Pu
γ-Pu
β-Pu
α-Pu
641°
610°
455°
442°
320°
280°
270°
125°
705°
590°
560°
278°
125°

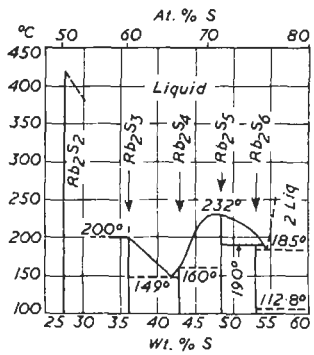
Pu–Zn


Wt. % Zn
°C
5
10
15
20
25
30
35
40
50
60
70
80
90
1100
1000
900
800
700
641°
600
500
400
300
200
100
0
Liquid
PuZn2
Pu2Zn9
PuZn8
Pu2Zn17
880°
830°
810°
695°
~3
ε - Pu
490°
δ' - Pu
~4
δ - Pu
419°
240°
γ - Pu
206°
β - Pu
122°
α - Pu
10
20
30
40
50
60
70
80
90
100
At. % Zn

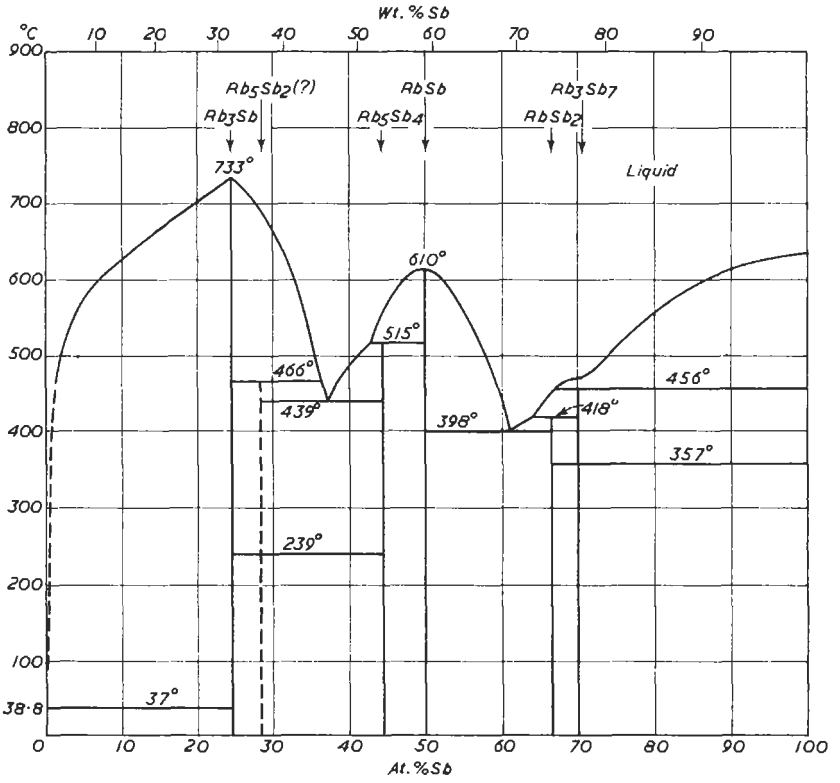
Pu–Zr


Wt.% Zr
1 3 5 10 15 20 25 30 40 50 60 70 80 90
°C
1800
1600
1400
1200
1000
800
600
400
200
0
Pu_6Zr
$PuZr_2$
Liquid
ε
δ
δ'
630°
415°
315°
200°
233°
116°
γ
β
α
αZr
10 20 30 40 50 60 70 80 90 100
At. % Pu

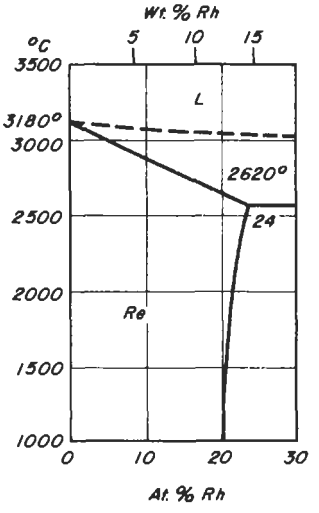
Rb–S


At. % S
°C 50 60 70 80
450
400
350
300
250
200
150
100
Liquid
Rb_2S_2
Rb_2S_3
Rb_2S_4
Rb_2S_5
Rb_2S_6
232°
200°
185°
160°
149°
190°
112·8°
2 Liq
25 30 35 40 45 50 55 60
Wt. % S

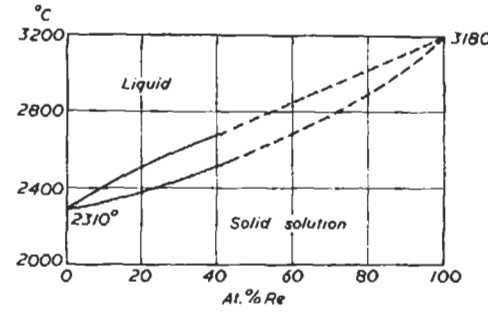
Rb–Sb


Wt. % Sb
°C
10 20 30 40 50 60 70 80 90
900
800
700
600
500
400
300
200
100
38·8
Rb5Sb2(?)
Rb3Sb
Rb5Sb4
RbSb
Rb3Sb7
RbSb2
Liquid
733°
610°
515°
466°
456°
439°
418°
398°
357°
239°
37°
0 10 20 30 40 50 60 70 80 90 100
At. %Sb

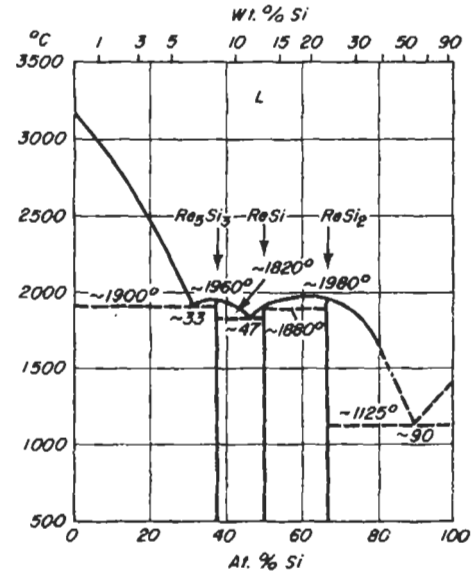
Re–Rh


Wt. % Rh
°C
5 10 15
3500
3180°
3000
2500
2000
1500
1000
L
2620°
24
Re
0 10 20 30
At. % Rh

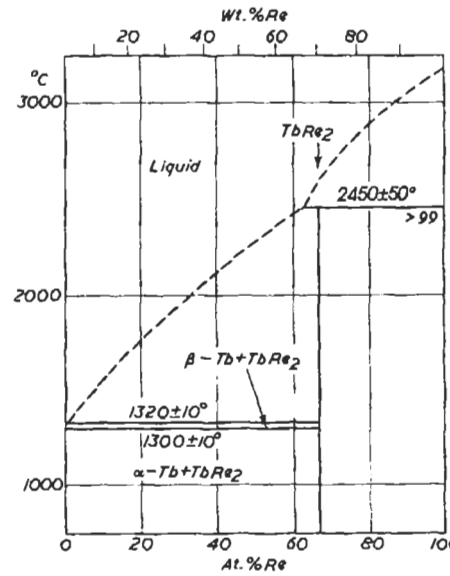
Re–Ru



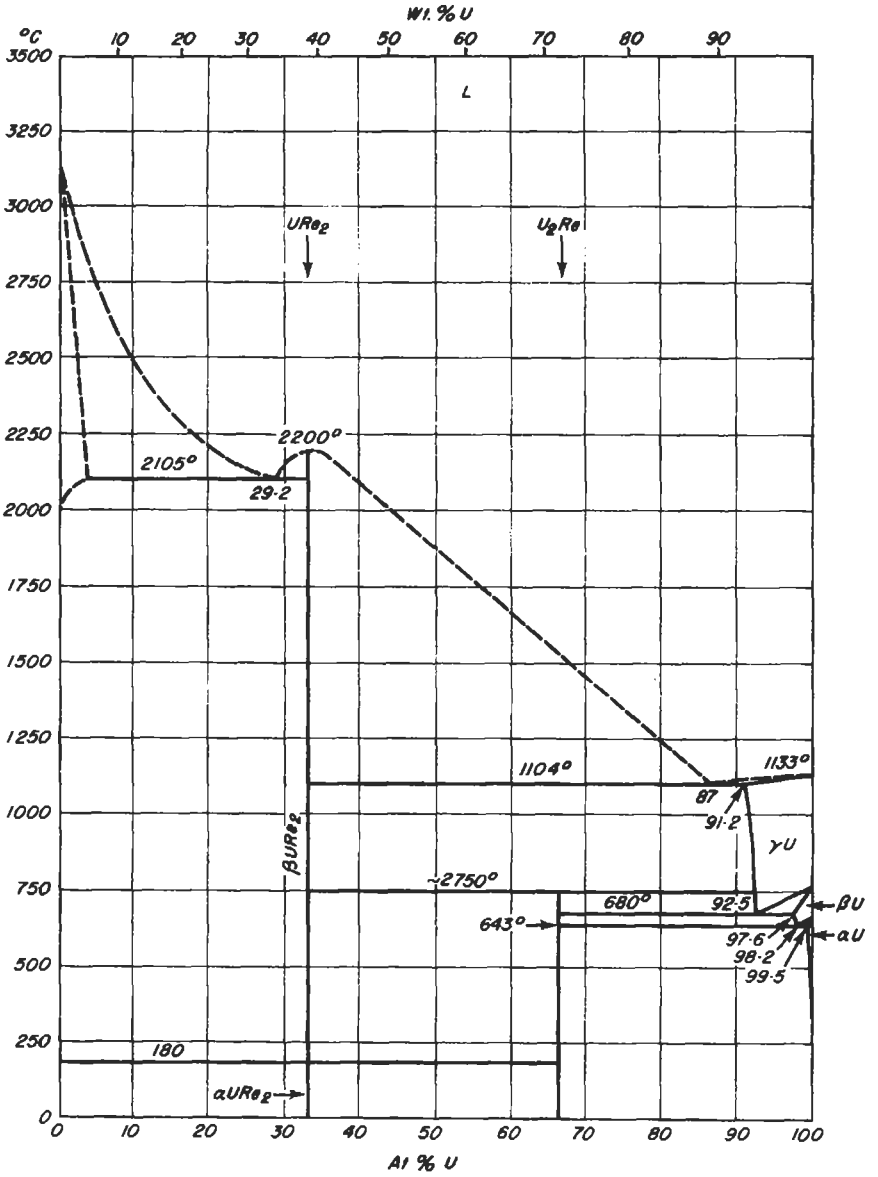
Re–Si



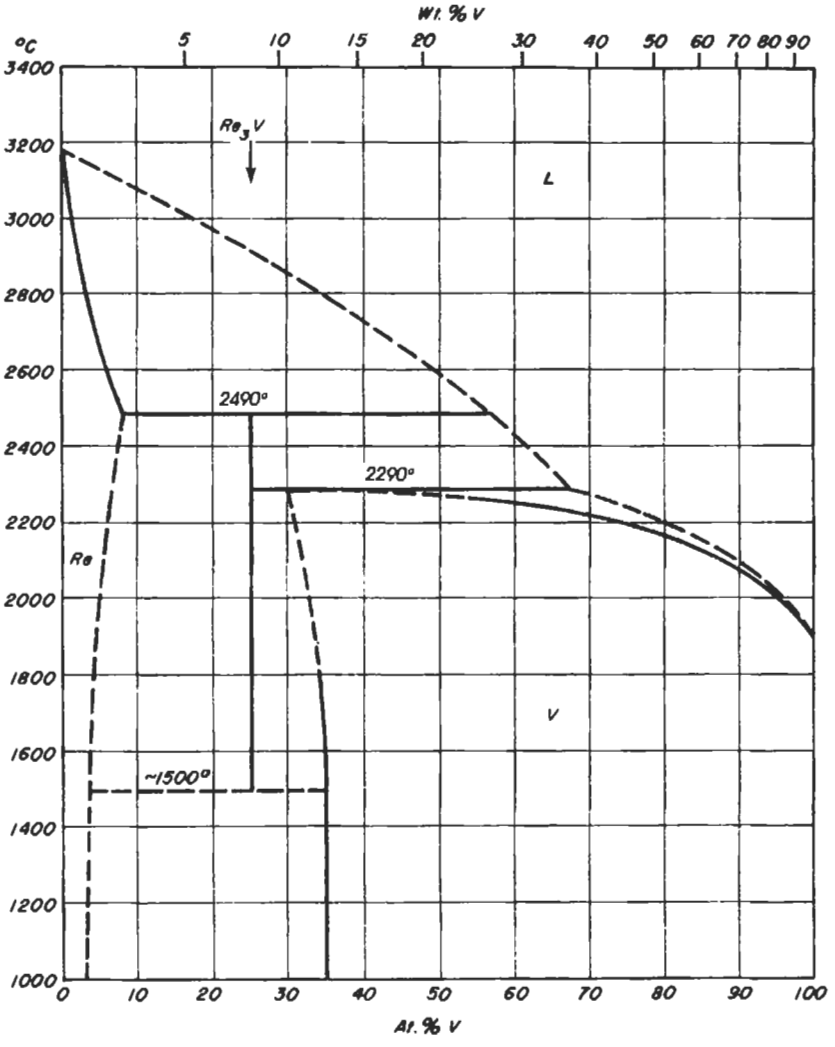
Re–Tb



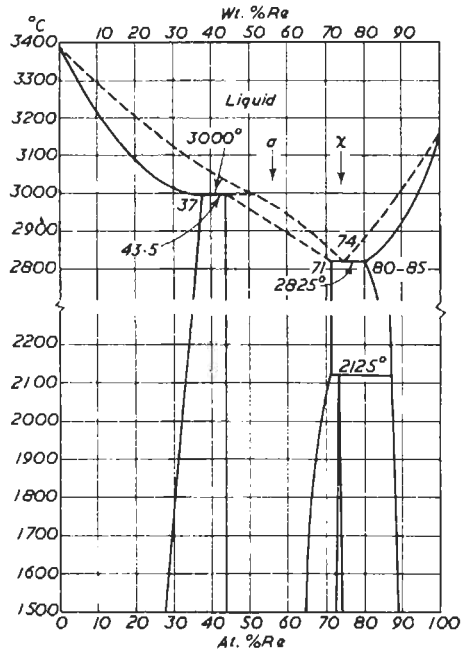
Re–U


Wt. % U
°C
10
20
30
40
50
60
70
80
90
3500
3250
3000
2750
2500
2250
2000
1750
1500
1250
1000
750
500
250
0
L
URe2
U2Re
2200°
2105°
29·2
1104°
1133°
87
91·2
γU
βURe2
~2750°
680°
92·5
βU
643°
97·6
αU
98·2
99·5
180
αURe2
0
10
20
30
40
50
60
70
80
90
100
At % U

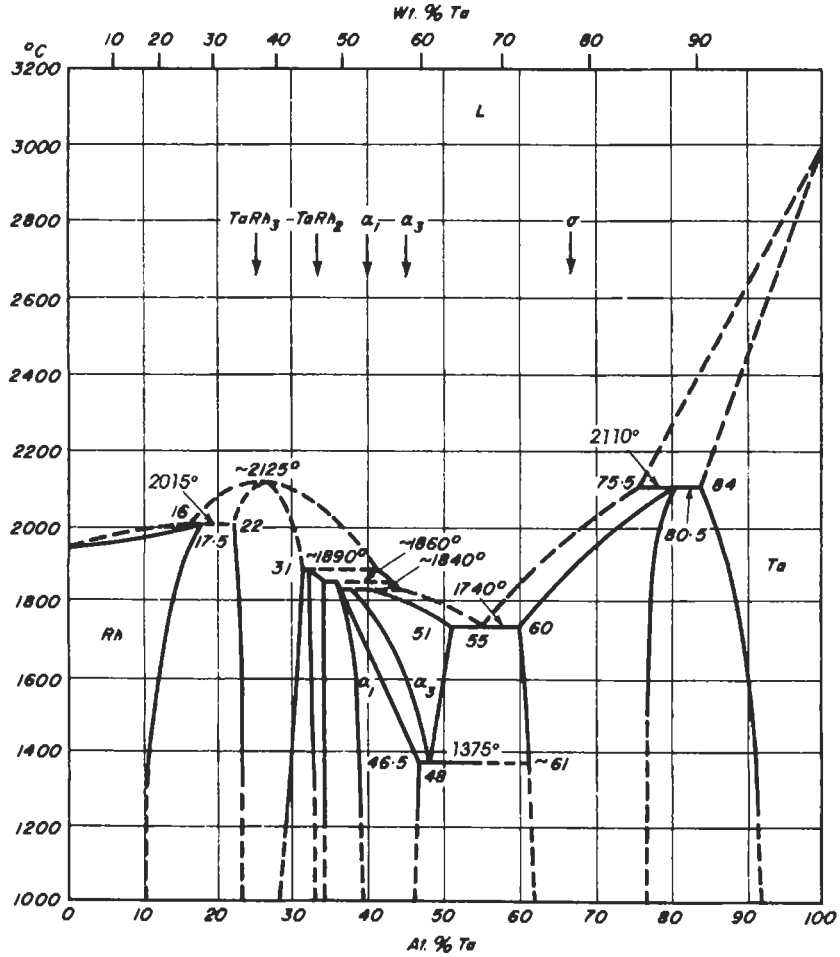
Re–V


Wt. % V
°C
5
10
15
20
30
40
50
60
70
80
90
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
Re_3V
L
2490°
2290°
Re
V
~1500°
0
10
20
30
40
50
60
70
80
90
100
At. % V

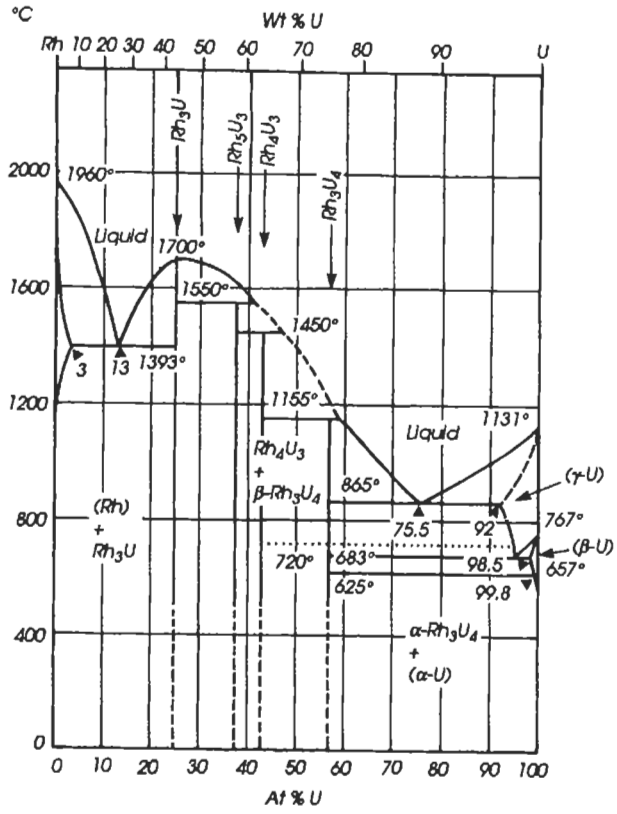
Re–W


°C
Wt. %Re
10 20 30 40 50 60 70 80 90
3400
3300
3200
3100
3000
2900
2800
2200
2100
2000
1900
1800
1700
1600
1500
Liquid
3000°
σ
χ
37
43·5
74
71
80–85
2825°
2125°
0 10 20 30 40 50 60 70 80 90 100
At. %Re

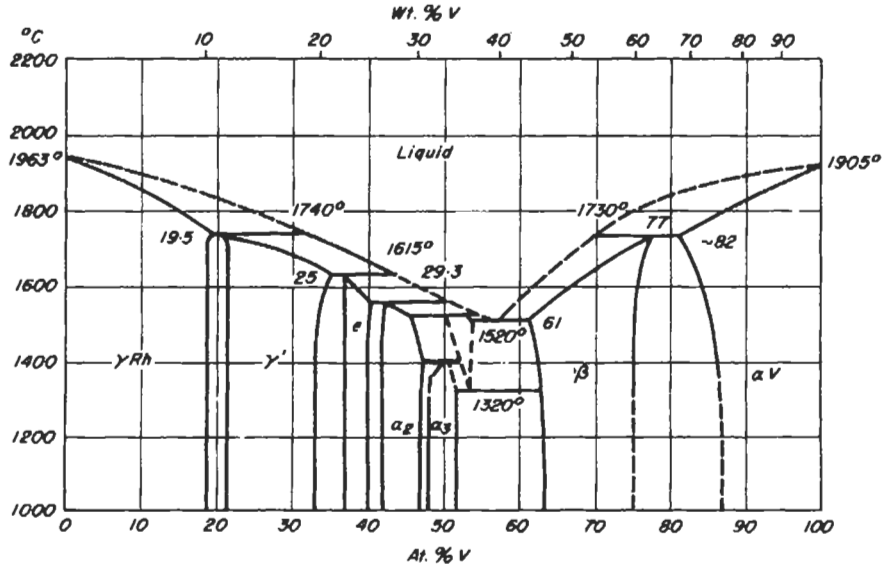
Rh–Ta


Wt. % Ta
°C
10 20 30 40 50 60 70 80 90
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
L
TaRh3
TaRh2
α1
α3
σ
2110°
75·5
84
2015°
~2125°
16
17·5
22
31
~1890°
~1860°
~1840°
1740°
80·5
Ta
Rh
51
55
60
α1
α3
1375°
46·5
48
~61
0 10 20 30 40 50 60 70 80 90 100
At. % Ta

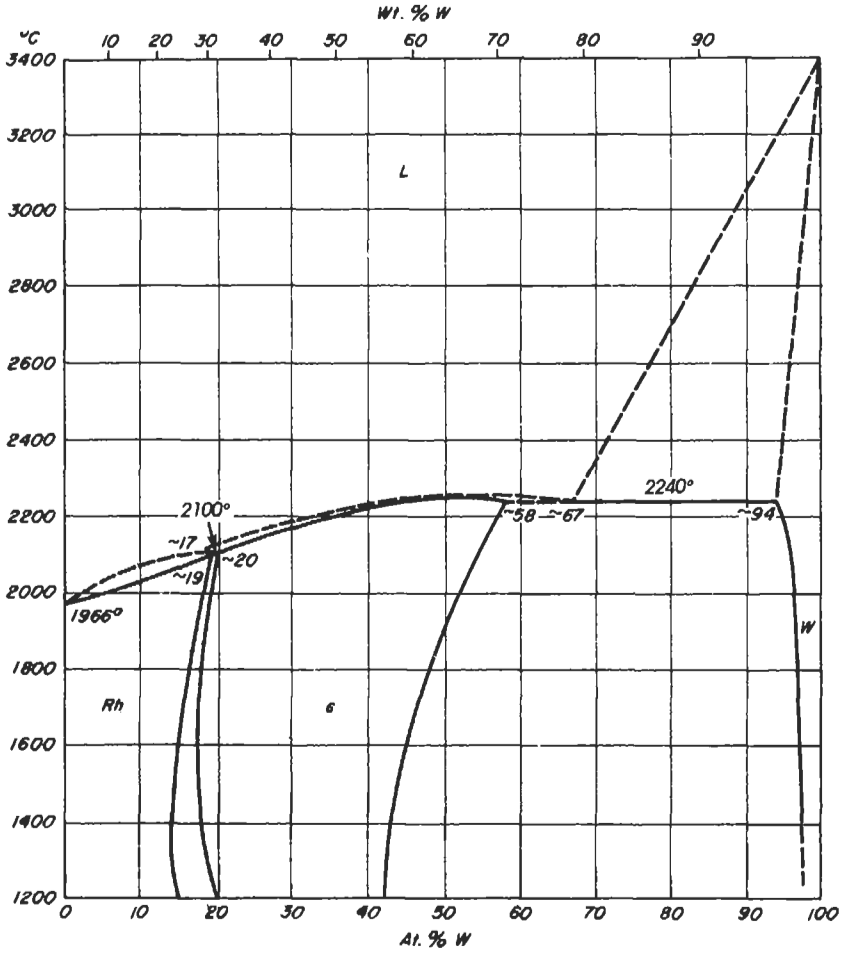
Rh–U


°C
Wt % U
Rh 10 20 30 40 50 60 70 80 90 U
2000
1600
1200
800
400
0
1960°
Liquid
1700°
1550°
1450°
1393°
1155°
1131°
865°
767°
720°
683°
657°
625°
3
13
Rh_3U
Rh_5U_3
Rh_4U_3
Rh_3U_4
Rh_4U_3 + β-Rh_3U_4
(Rh) + Rh_3U
α-Rh_3U_4 + (α-U)
(γ-U)
(β-U)
75.5
92
98.5
99.8
0 10 20 30 40 50 60 70 80 90 100
At % U

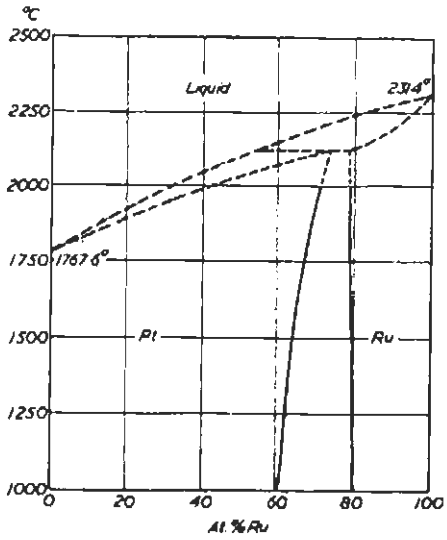
Rh–V


Wt. % V
°C
10 20 30 40 50 60 70 80 90
2200
2000
1800
1600
1400
1200
1000
1963°
Liquid
1740°
1730°
1905°
19·5
1615°
29·3
25
77
~82
e
1520°
61
γRh
γ'
γβ
α V
1320°
α_E
α_3
0 10 20 30 40 50 60 70 80 90 100
At. % V

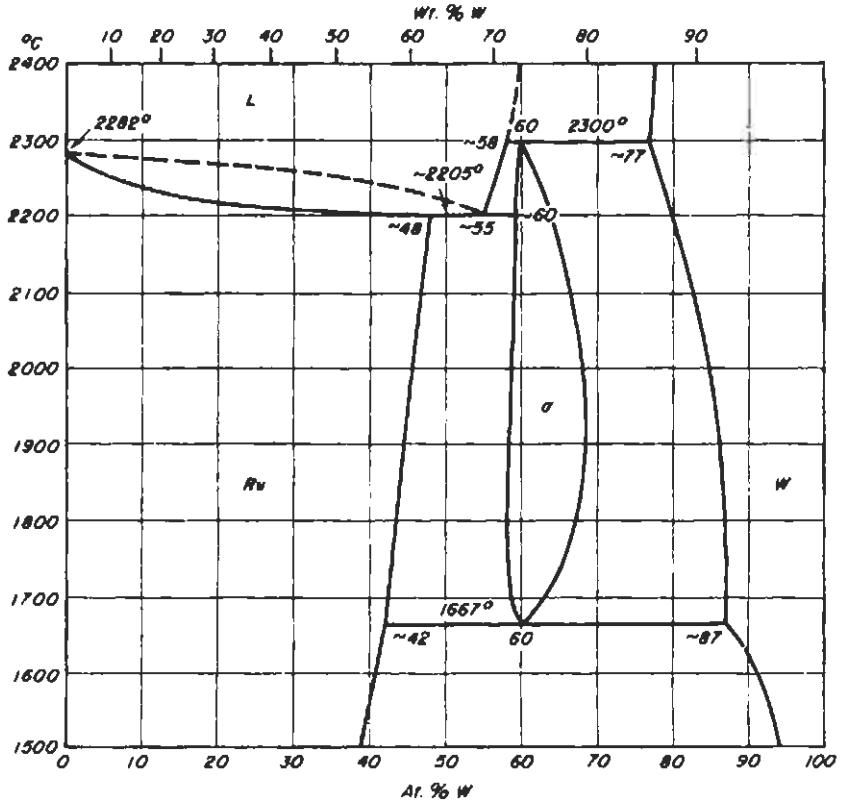
Rh–W


Wt. % W
°C
10
20
30
40
50
60
70
80
90
3400
3200
3000
2800
2600
2400
2200
2000
1800
1600
1400
1200
L
2100°
~17
~19
~20
1966°
2240°
~58
~67
~94
W
Rh
ε
0
10
20
30
40
50
60
70
80
90
100
At. % W

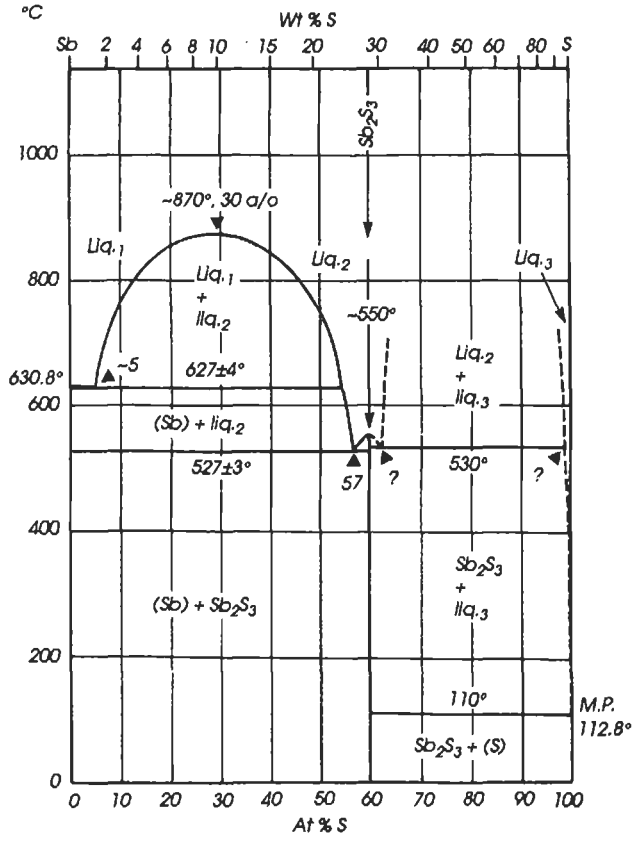
Ru–Pt


°C
2500
2250
2000
1750
1500
1250
1000
Liquid
2314°
1767.6°
Pt
Ru
0
20
40
60
80
100
At. % Ru

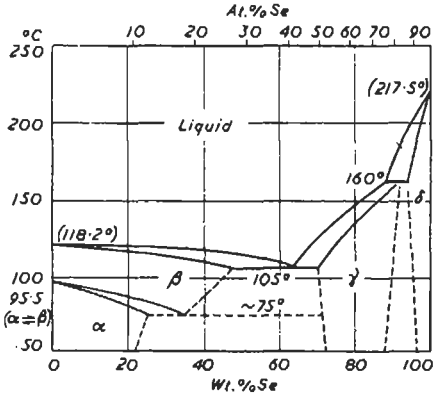
Ru–W


Wt. % W
°C
10
20
30
40
50
60
70
80
90
2400
2300
2200
2100
2000
1900
1800
1700
1600
1500
L
2282°
~58
60
2300°
~77
~2205°
~48
~55
~60
σ
Ru
W
1667°
~42
60
~87
0
10
20
30
40
50
60
70
80
90
100
At. % W

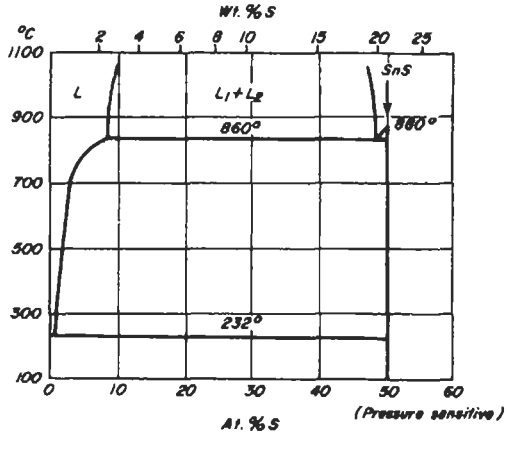
S–Sb


°C
Wt % S
Sb 2 4 6 8 10 15 20 30 40 50 60 80 S
1000
800
630.8°
600
400
200
0
Sb_2S_3
~870°, 30 a/o
Liq.1
Liq.1 + liq.2
Liq.2
Liq.3
~550°
~5
627±4°
Liq.2 + liq.3
(Sb) + liq.2
527±3°
57
?
530°
?
Sb_2S_3 + liq.3
(Sb) + Sb_2S_3
110°
M.P. 112.8°
Sb_2S_3 + (S)
0 10 20 30 40 50 60 70 80 90 100
At % S

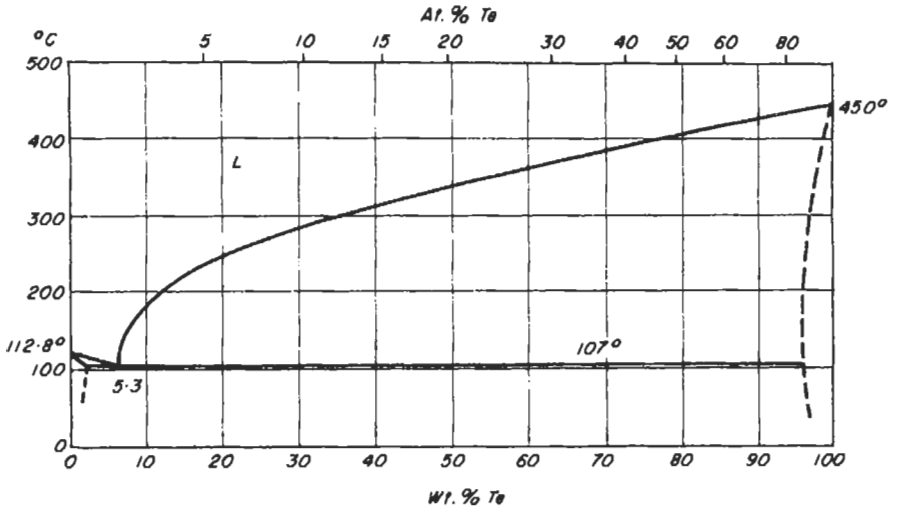
S–Se


At.% Se
°C
10 20 30 40 50 60 70 90
250
200
150
100
95·5
(α⇌β)
50
Liquid
(217·5°)
160°
δ
(118·2°)
β
105°
γ
~75°
α
0 20 40 60 80 100
Wt.% Se

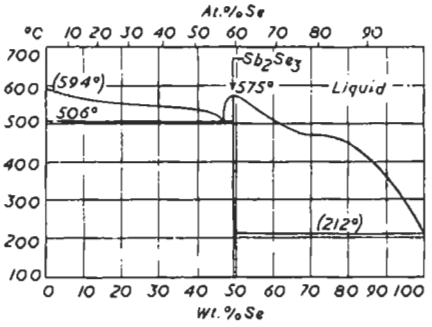
S–Sn


Wt. % S
°C
2 4 6 8 10 15 20 25
1100
900
700
500
300
100
L
L_1+L_2
SnS
860°
860°
232°
0 10 20 30 40 50 60
At. % S
(Pressure sensitive)

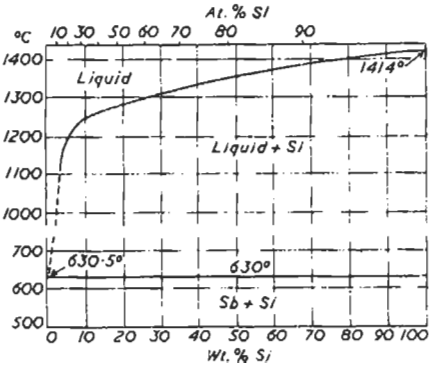
S–Te



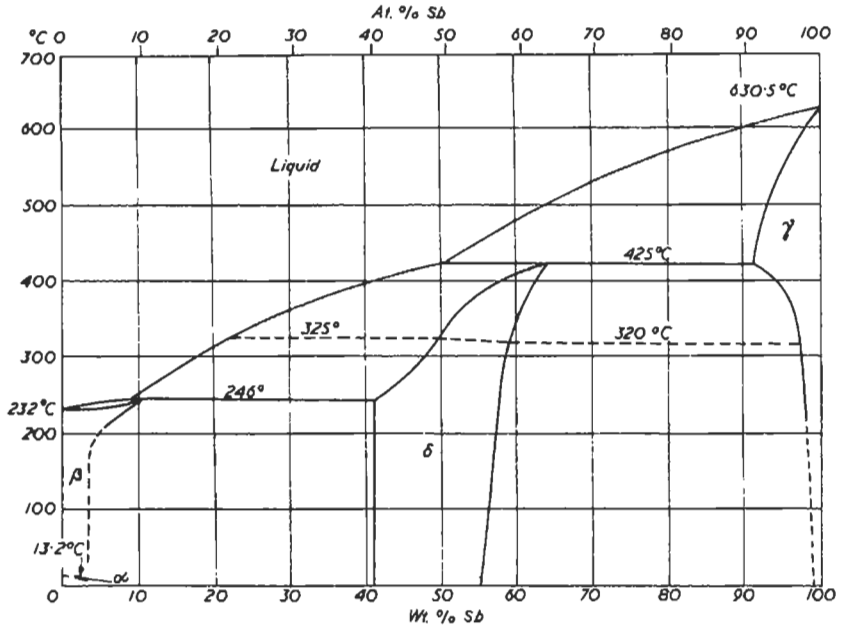
Sb–Se



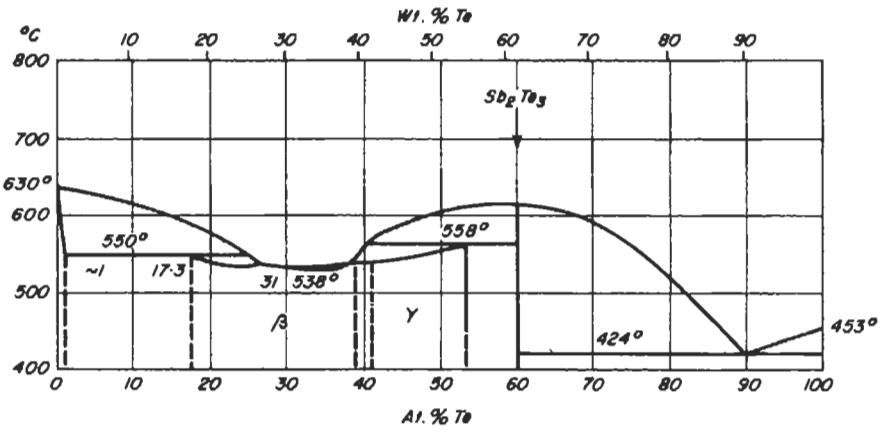
Sb–Si



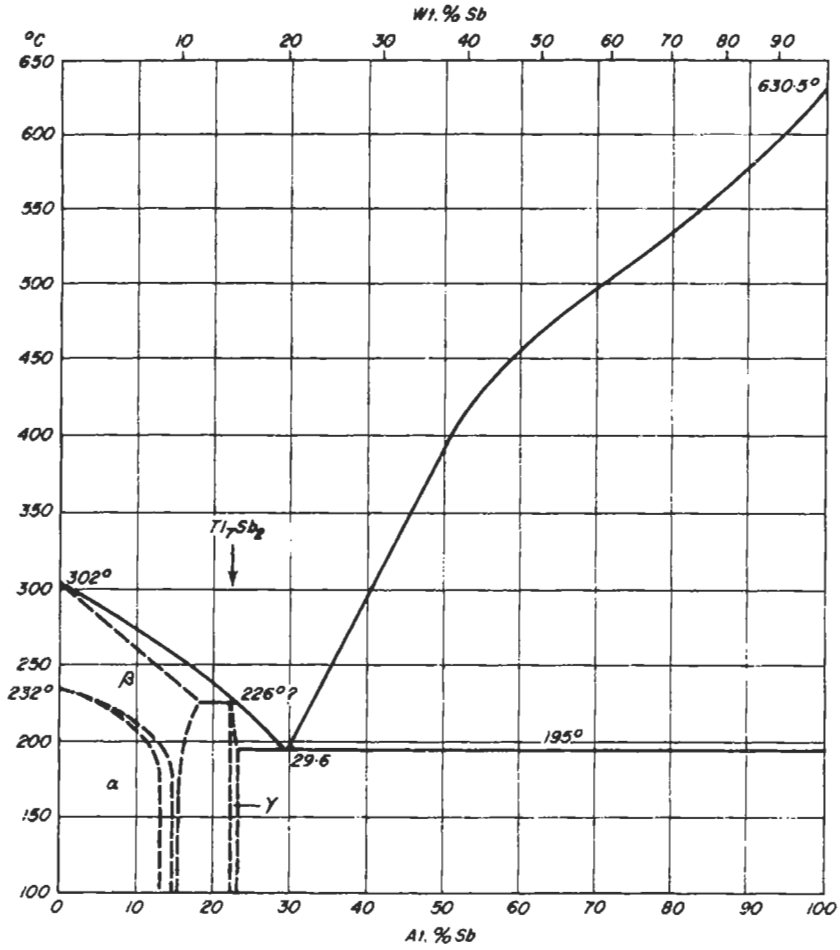
Sb–Sn


At. % Sb
°C
Liquid
630·5 °C
425°C
325°
320 °C
246°
232°C
13·2°C
α
β
γ
δ
Wt. % Sb

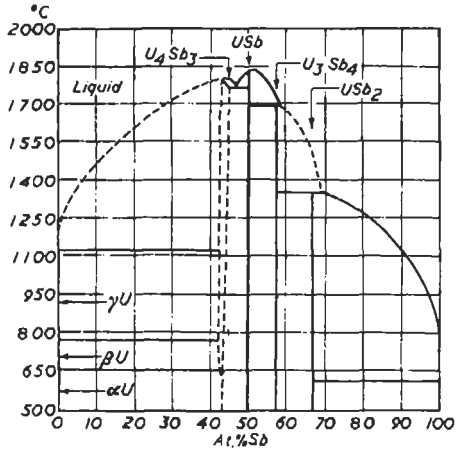
Sb–Te


Wt. % Te
°C
Sb2Te3
630°
550°
558°
538°
424°
453°
β
γ
At. % Te

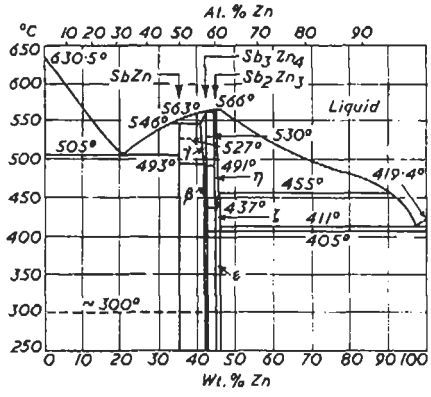
Sb–Tl


Wt. % Sb
°C
10
20
30
40
50
60
70
80
90
650
600
550
500
450
400
350
300
250
232°
200
150
100
630·5°
Tl_7Sb_2
302°
β
226°?
195°
29·6
α
γ
0
10
20
30
40
50
60
70
80
90
100
At. % Sb

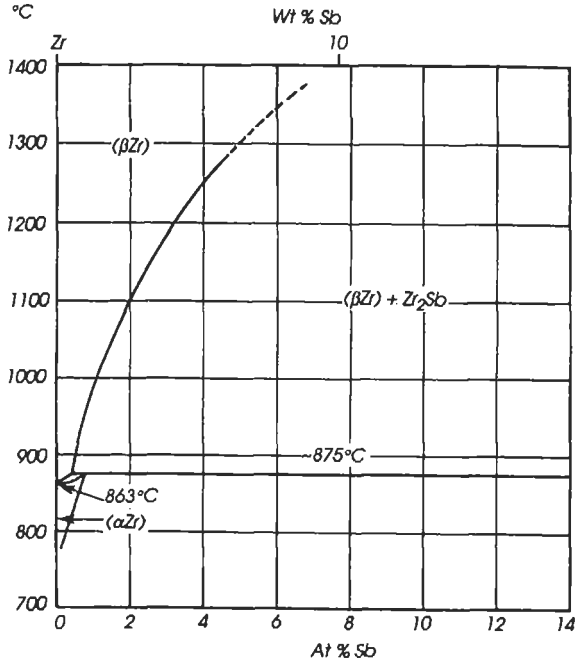
Sb–U



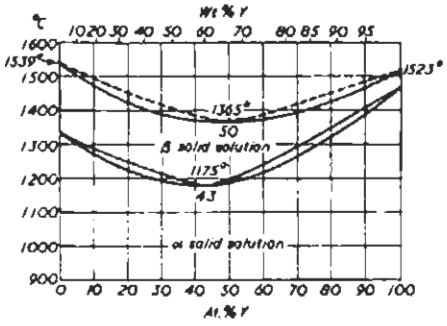
Sb–Zn



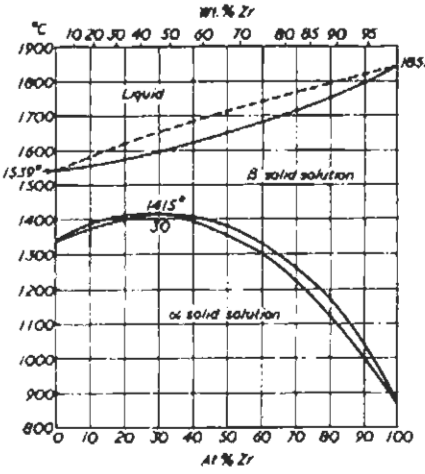
Sb–Zr



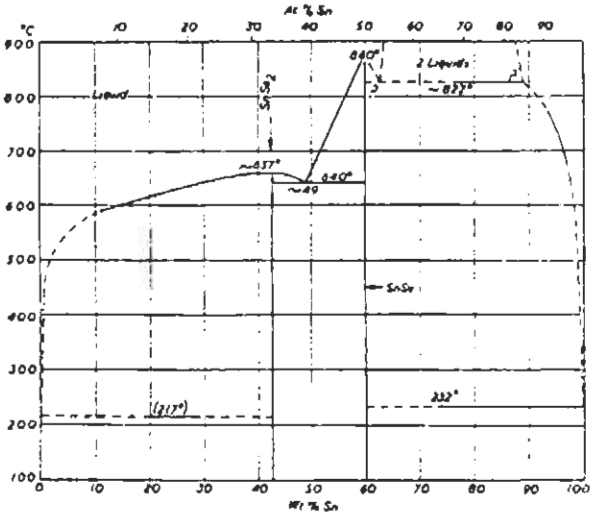
Sc–Y



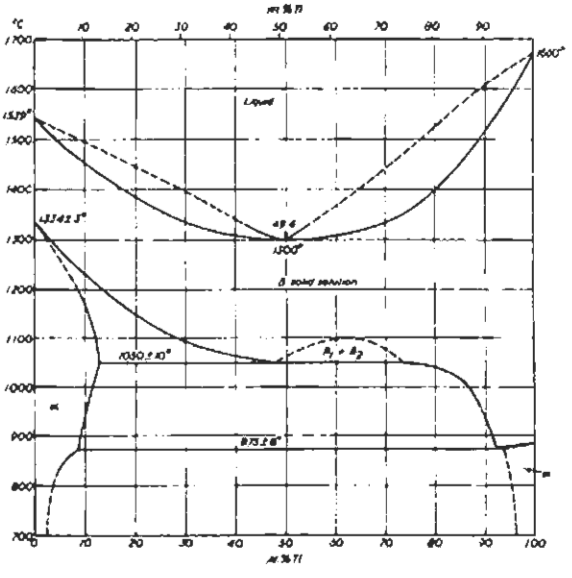
Sc–Zr



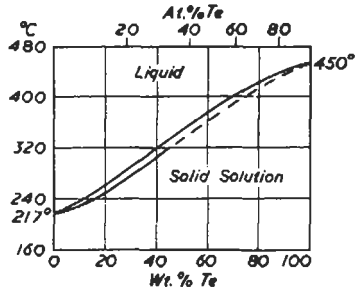
Se–Sn



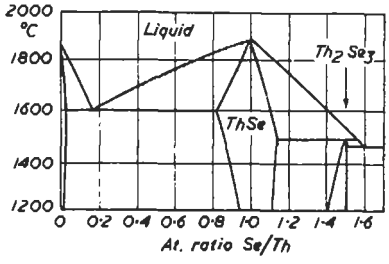
Sc–Ti



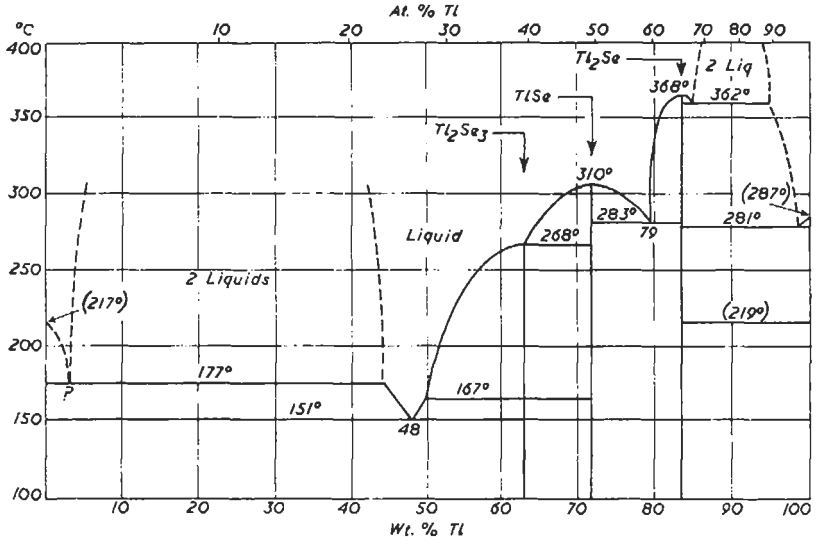
Se–Te



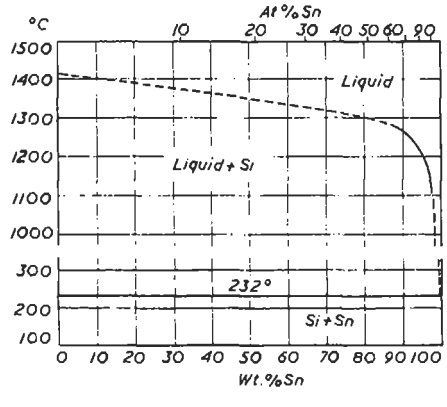
Se–Th



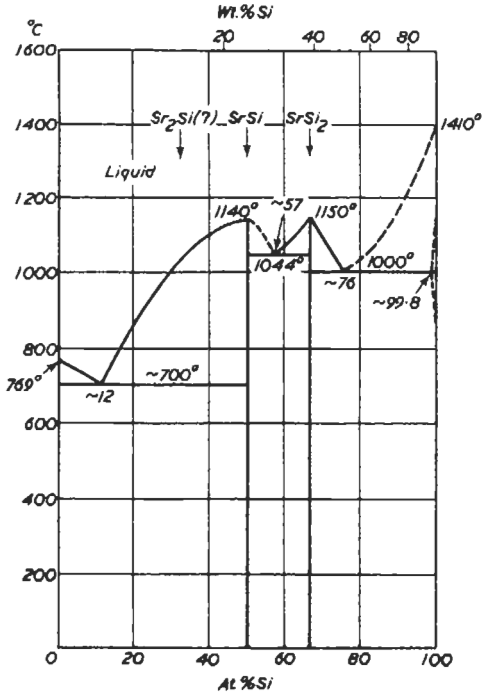
Se–Tl



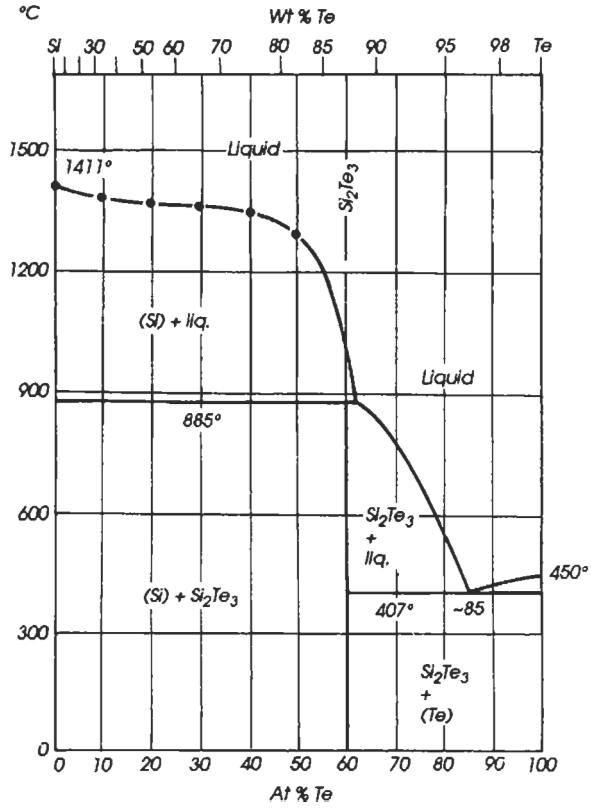
Si–Sn



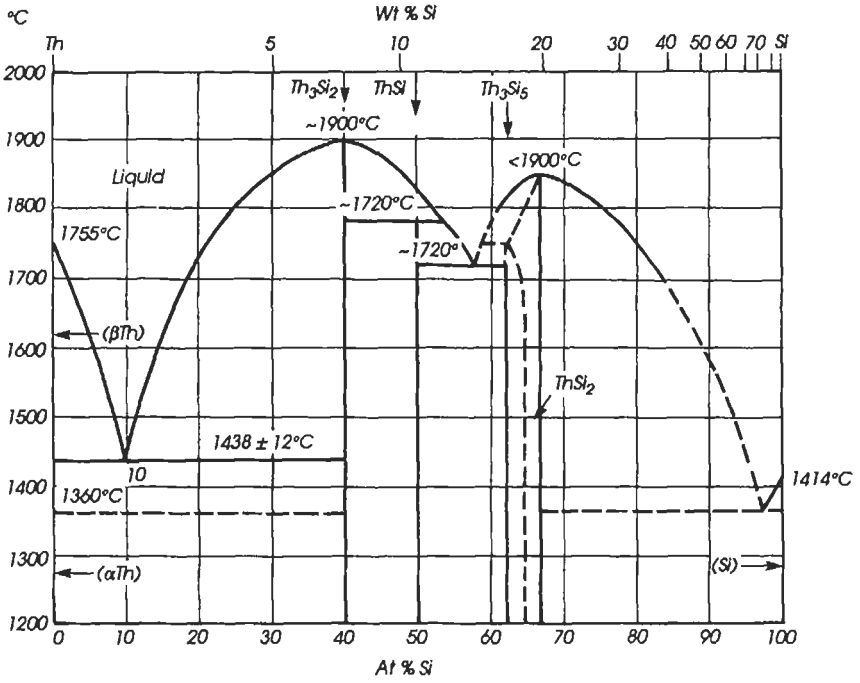
Si–Sr


°C
Wt.% Si
20
40
60
80
1600
1400
1200
1000
800
600
400
200
0
20
40
60
80
100
At %Si
$Sr_2Si(?)$
SrSi
$SrSi_2$
1410°
Liquid
1140°
~57
1150°
1044°
1000°
~76
~99·8
769°
~12
~700°

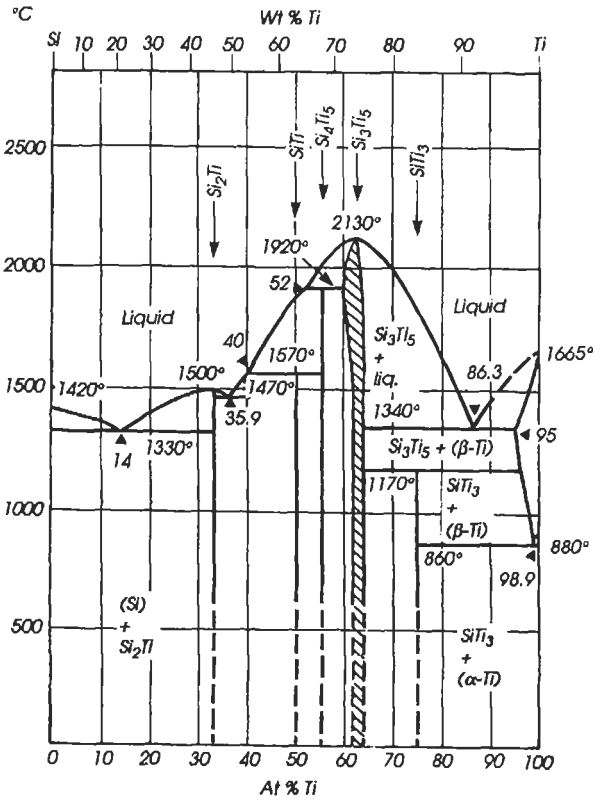
Si–Te


°C
Wt % Te
Si
30
50
60
70
80
85
90
95
98
Te
1500
1200
900
600
300
0
10
20
30
40
50
60
70
80
90
100
At % Te
Liquid
1411°
Si_2Te_3
(Si) + liq.
Liquid
885°
Si_2Te_3
+
liq.
450°
(Si) + Si_2Te_3
407°
~85
Si_2Te_3
+
(Te)

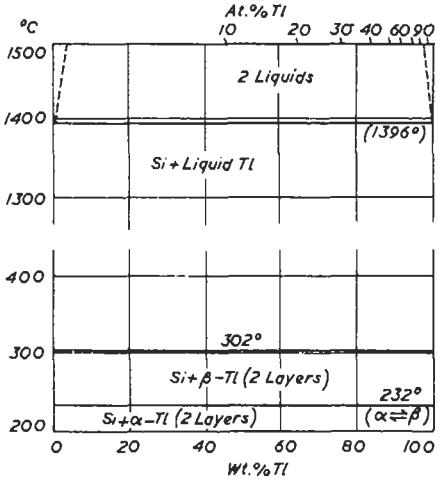
Si–Th


°C
Wt % Si
Th
5
10
20
30
40
50
60
70
Si
2000
1900
1800
1700
1600
1500
1400
1300
1200
Th_3Si_2
ThSi
Th_3Si_5
~1900°C
<1900°C
Liquid
~1720°C
~1720°
1755°C
(βTh)
$ThSi_2$
1438 ± 12°C
10
1360°C
1414°C
(αTh)
(Si)
0
10
20
30
40
50
60
70
80
90
100
At % Si

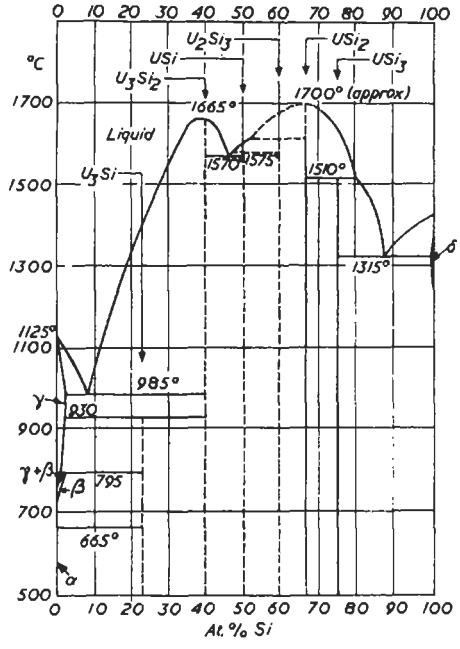
Si–Ti


°C
Wt % Ti
Si
10
20
30
40
50
60
70
80
90
Ti
2500
2000
1500
1000
500
Si_2Ti
SiTi
Si_4Ti_5
Si_3Ti_5
$SiTi_3$
2130°
1920°
52
Liquid
Liquid
40
1570°
Si_3Ti_5
+
liq.
1665°
86.3
1500°
1420°
1470°
35.9
1340°
14
1330°
Si_3Ti_5 + (β-Ti)
95
1170°
$SiTi_3$
+
(β-Ti)
880°
860°
98.9
(Si)
+
Si_2Ti
$SiTi_3$
+
(α-Ti)
0
10
20
30
40
50
60
70
80
90
100
At % Ti

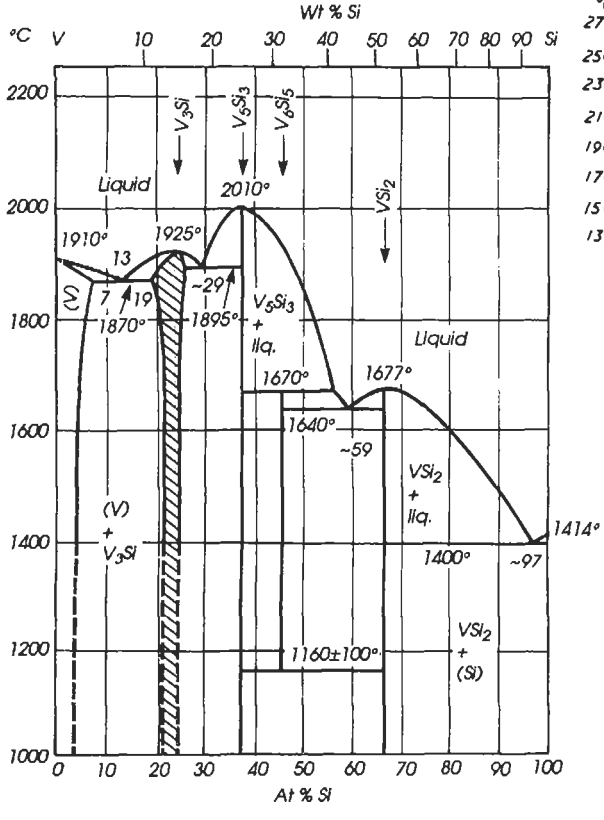
Si–Tl



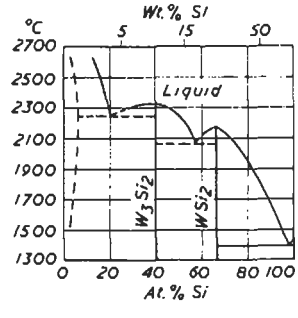
Si–U



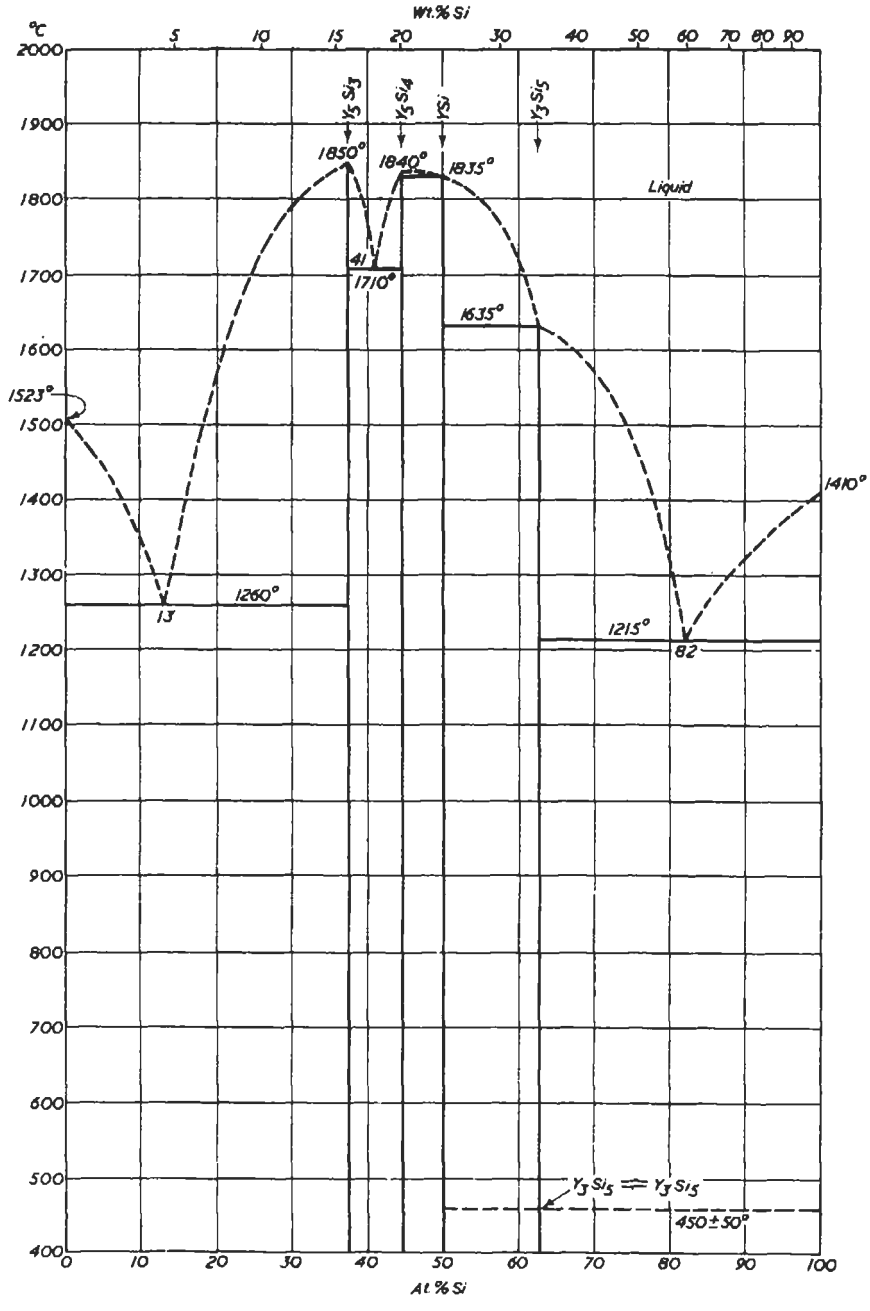
Si–V

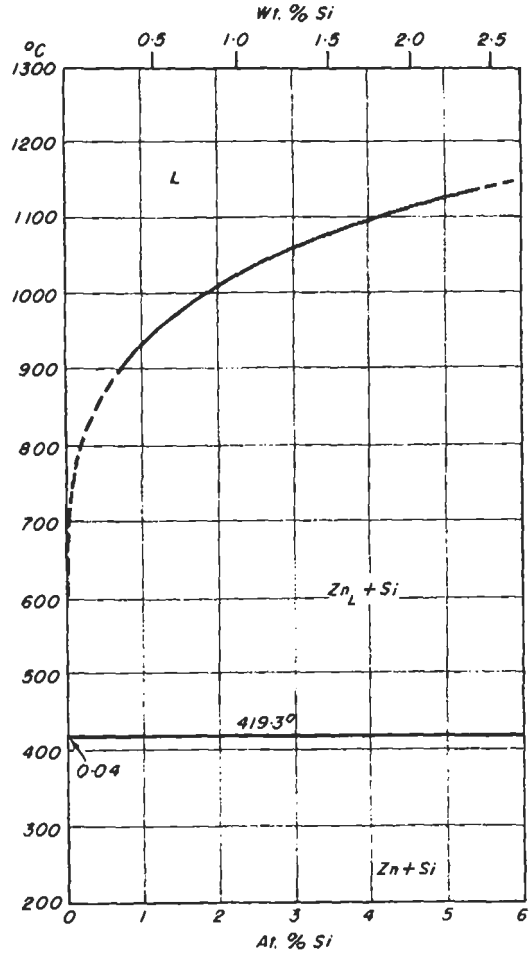


Si–W

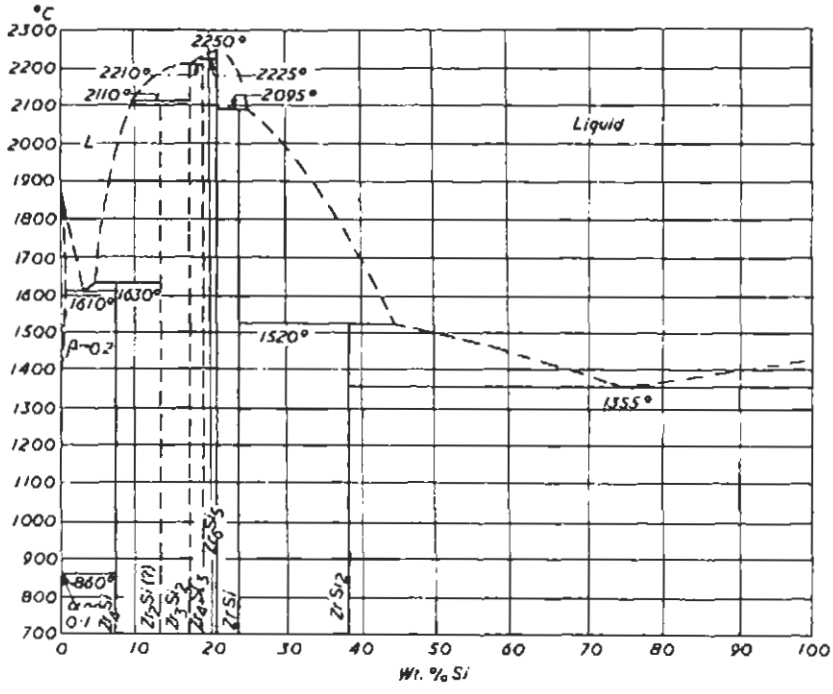


Si–Y

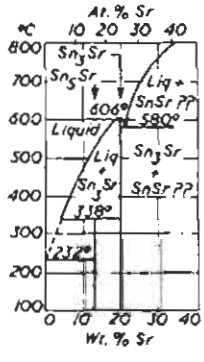

°C
Wt.% Si
At.% Si
Y5 Si3
Y5 Si4
YSi
Y3 Si5
1850°
1840°
1835°
Liquid
41
1710°
1635°
1523°
1410°
13
1260°
1215°
82
Y3 Si5 ⇌ Y3 Si5
450±50°


Wt. % Si
°C
0·5
1·0
1·5
2·0
2·5
1300
1200
1100
1000
900
800
700
600
500
400
300
200
L
$Zn_L + Si$
419·3°
0·04
Zn + Si
0
1
2
3
4
5
6
At. % Si
Si–Zn

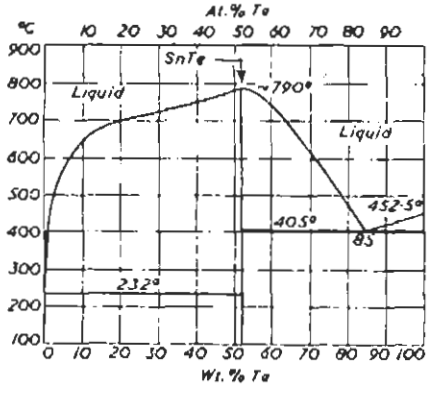
Si–Zr



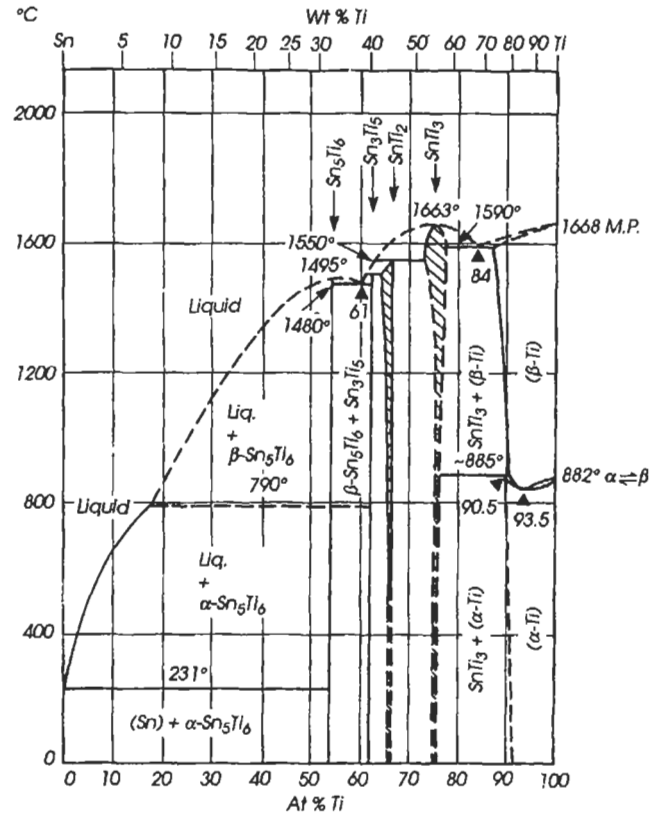
Sn–Sr



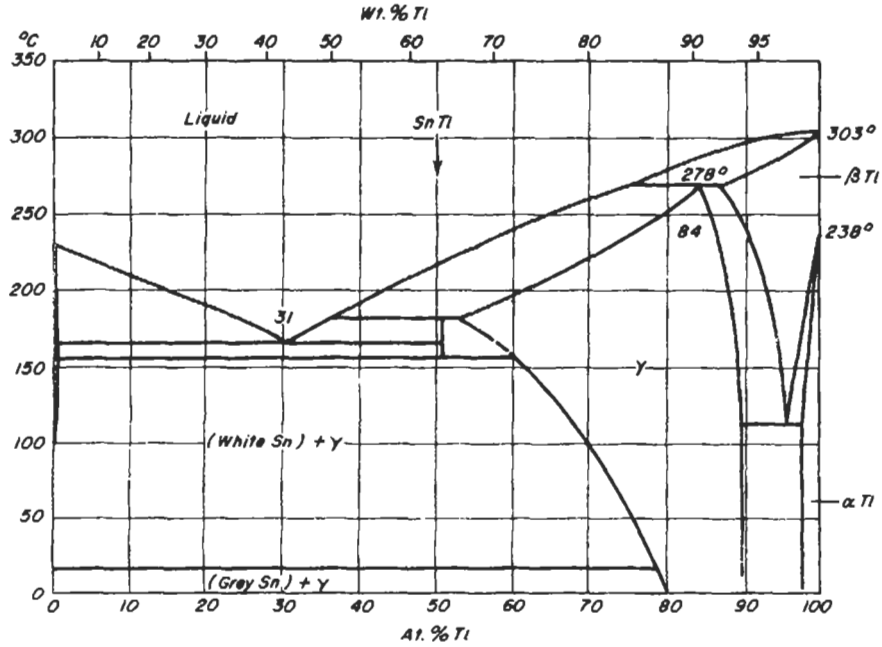
Sn–Te



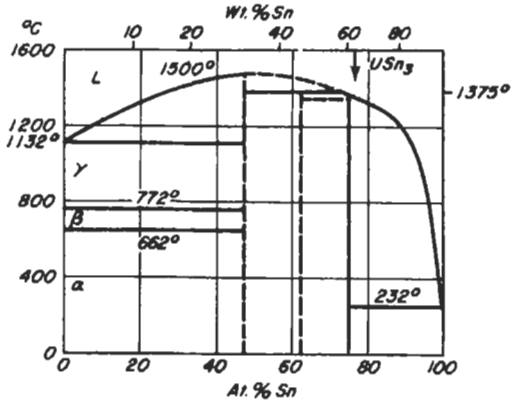
Sn–Ti


°C
Wt % Ti
Sn 5 10 15 20 25 30 40 50 60 70 80 90 Ti
2000
1600
1200
800
400
0
Sn_5Ti_6
Sn_3Ti_5
$SnTi_2$
$SnTi_3$
1663°
1590°
1668 M.P.
1550°
1495°
84
61
1480°
Liquid
Liq. + β-Sn_5Ti_6
790°
β-Sn_5Ti_6 + Sn_3Ti_5
$SnTi_3$ + (β-Ti)
(β-Ti)
~885°
882° α⇌β
Liquid
90.5
93.5
Liq. + α-Sn_5Ti_6
231°
(Sn) + α-Sn_5Ti_6
$SnTi_3$ + (α-Ti)
(α-Ti)
0 10 20 30 40 50 60 70 80 90 100
At % Ti

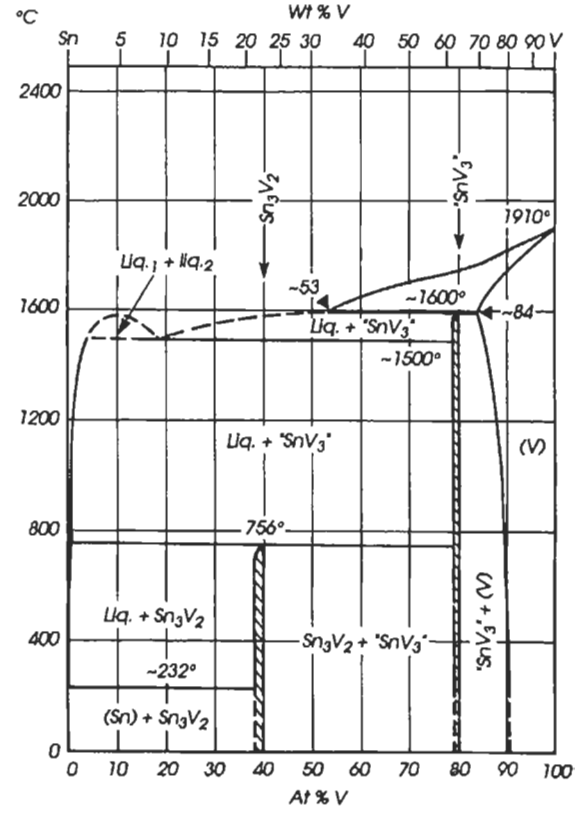
Sn–Tl


Wt. % Tl
°C
10 20 30 40 50 60 70 80 90 95
350
300
250
200
150
100
50
0
Liquid
Sn Tl
303°
278°
βTl
84
238°
31
γ
(White Sn) + γ
αTl
(Grey Sn) + γ
0 10 20 30 40 50 60 70 80 90 100
At. % Tl

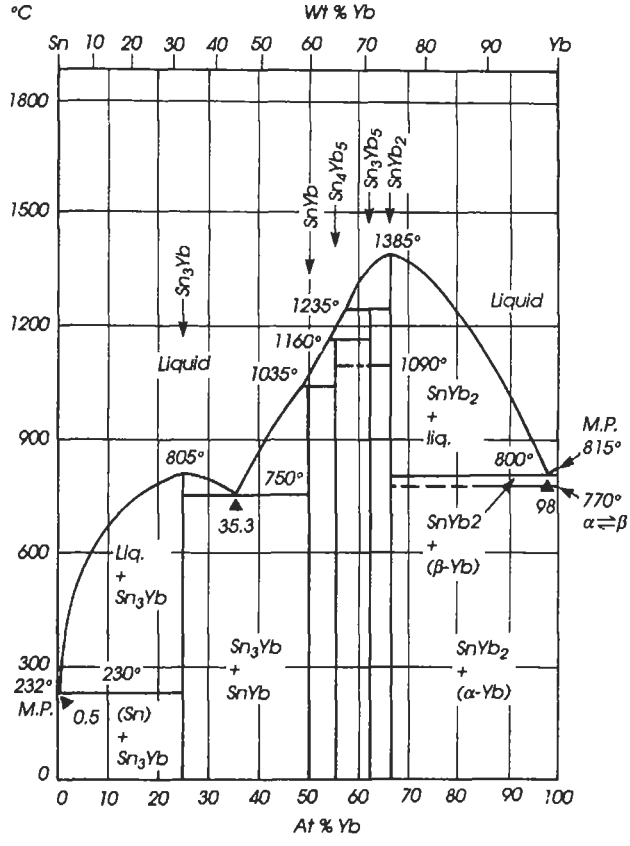
Sn–U


°C
Wt. % Sn
10
20
40
60
80
1600
1200
800
400
0
L
1500°
USn3
1375°
1132°
γ
772°
β
662°
α
232°
0
20
40
60
80
100
At. % Sn

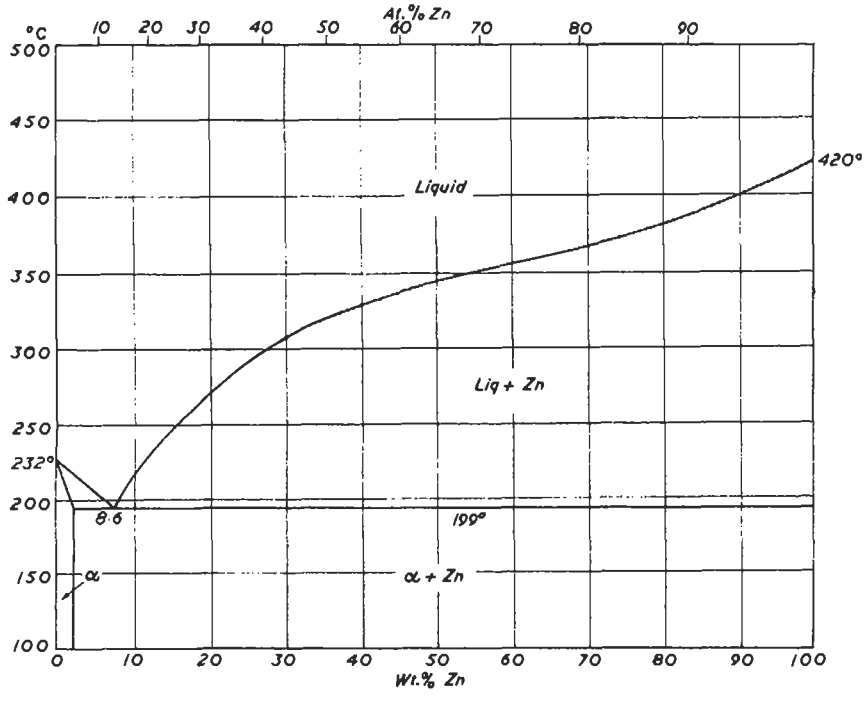
Sn–V


°C
Wt % V
Sn
5
10
15
20
25
30
40
50
60
70
80
90
V
2400
2000
1600
1200
800
400
0
Sn3V2
'SnV3'
1910°
Liq.1 + liq.2
~53
~1600°
~84
Liq. + 'SnV3'
~1500°
Liq. + 'SnV3'
(V)
756°
Liq. + Sn3V2
Sn3V2 + 'SnV3'
'SnV3' + (V)
~232°
(Sn) + Sn3V2
0
10
20
30
40
50
60
70
80
90
100
At % V

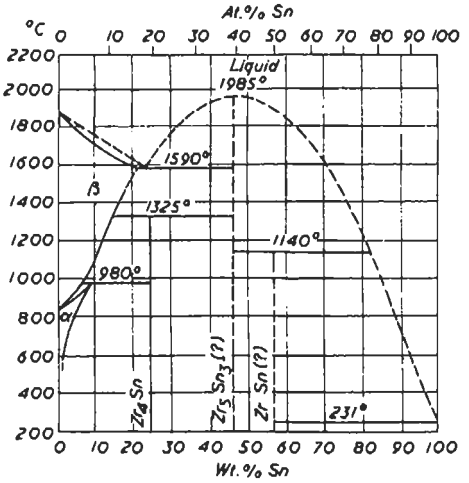
Sn–Yb


°C
Wt % Yb
Sn 10 20 30 40 50 60 70 80 90 Yb
1800
1500
1200
900
600
300
232°
M.P.
0
0 10 20 30 40 50 60 70 80 90 100
At % Yb
Sn3Yb
SnYb
Sn4Yb5
Sn3Yb5
SnYb2
1385°
1235°
1160°
1090°
1035°
805°
750°
230°
0.5
35.3
98
800°
770°
α⇌β
M.P.
815°
Liquid
Liquid
SnYb2
+
liq.
SnYb2
+
(β-Yb)
Liq.
+
Sn3Yb
Sn3Yb
+
SnYb
SnYb2
+
(α-Yb)
(Sn)
+
Sn3Yb

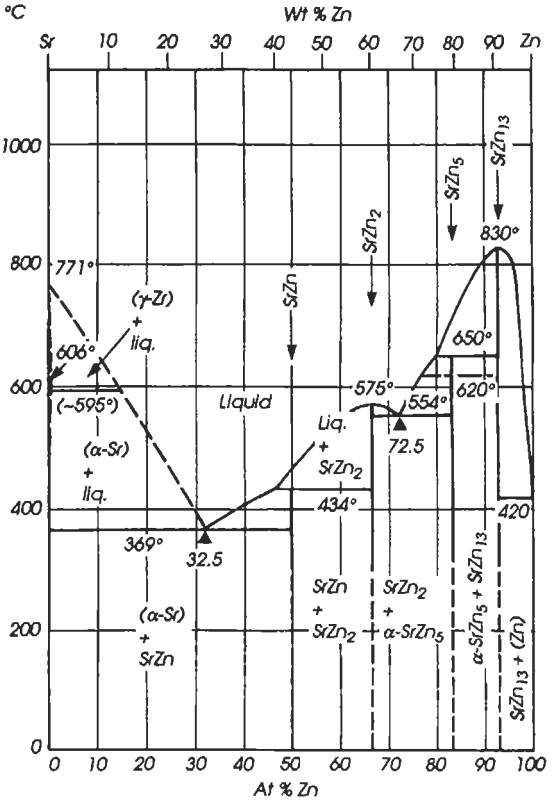
Sn–Zn


°C
At.% Zn
10 20 30 40 50 60 70 80 90
500
450
400
350
300
250
232°
200
150
100
0 10 20 30 40 50 60 70 80 90 100
Wt.% Zn
Liquid
420°
Liq + Zn
8·6
199°
α
α + Zn

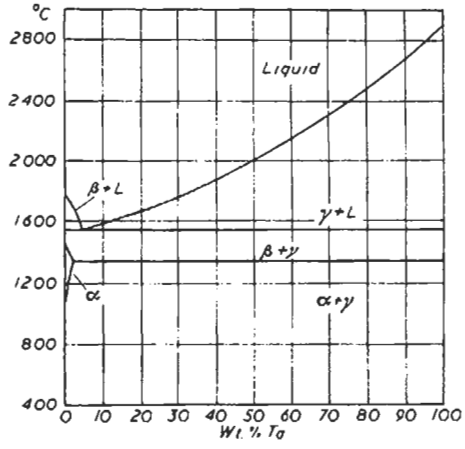
Sn–Zr


At.% Sn
°C
Liquid
1985°
1590°
β
1325°
1140°
980°
α
Zr4Sn
Zr5Sn4 (?)
Zr Sn (?)
231°
Wt.% Sn

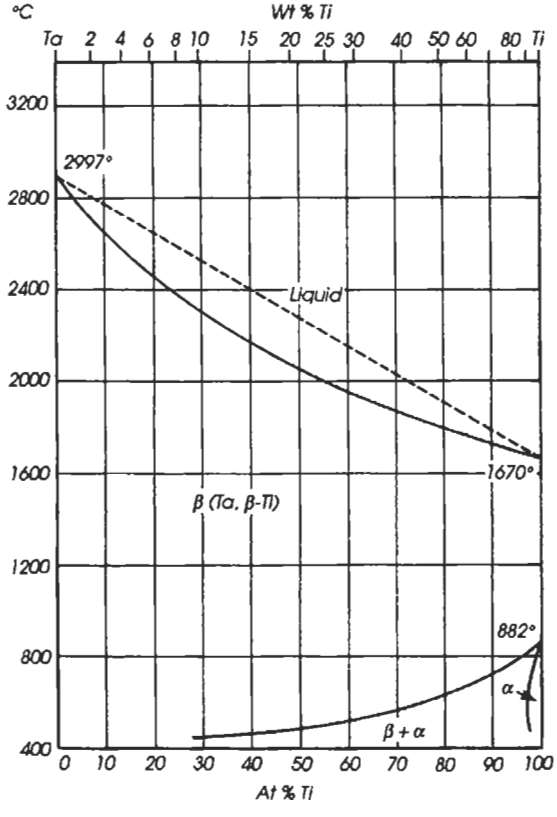
Sr–Zn


°C
Wt % Zn
Sr
Zn
771°
(γ-Zr)
+
liq.
606°
(~595°)
(α-Sr)
+
liq.
Liquid
SrZn
SrZn2
SrZn5
SrZn13
830°
650°
575°
554°
620°
Liq.
+
SrZn2
72.5
434°
420°
369°
32.5
SrZn
+
SrZn2
SrZn2
+
α-SrZn5
α-SrZn5 + SrZn13
SrZn13 + (Zn)
(α-Sr)
+
SrZn
At % Zn

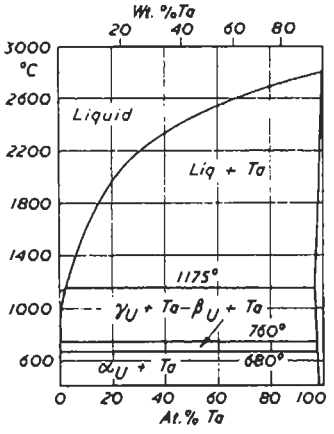
Ta–Th


°C
2800
2400
2000
1600
1200
800
400
Liquid
β + L
γ + L
β + γ
α
α + γ
0 10 20 30 40 50 60 70 80 90 100
Wt. % Ta

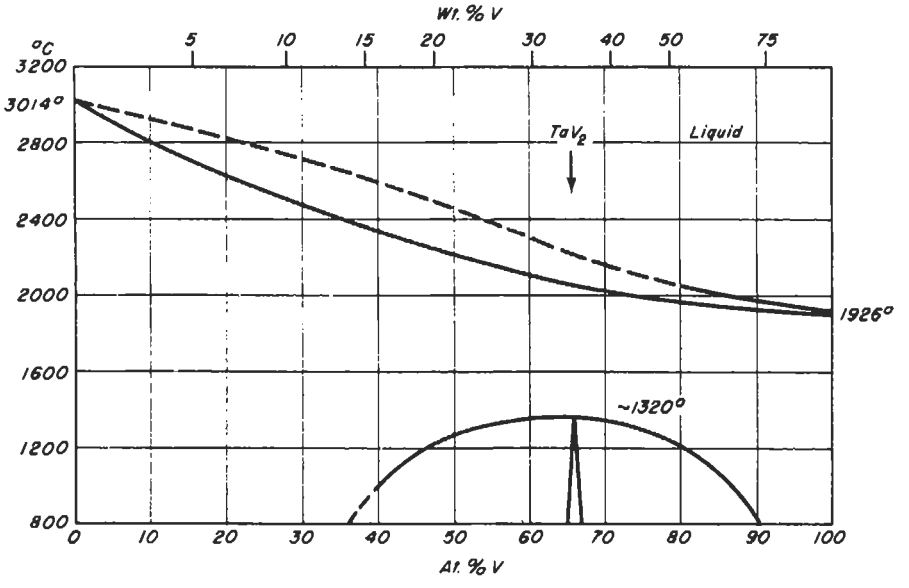
Ta–Ti


°C
Wt % Ti
Ta 2 4 6 8 10 15 20 25 30 40 50 60 80 Ti
3200
2800
2400
2000
1600
1200
800
400
2997°
Liquid
1670°
β (Ta, β-Ti)
882°
α
β + α
0 10 20 30 40 50 60 70 80 90 100
At % Ti

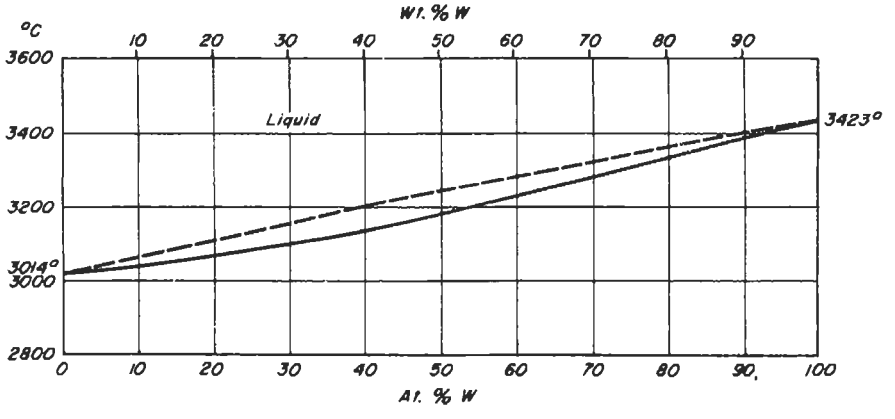
Ta–U


Wt. %Ta
20
40
60
80
3000
°C
2600
2200
1800
1400
1000
600
Liquid
Liq + Ta
1175°
γU + Ta
β U + Ta
760°
αU + Ta
680°
0
20
40
60
80
100
At.% Ta

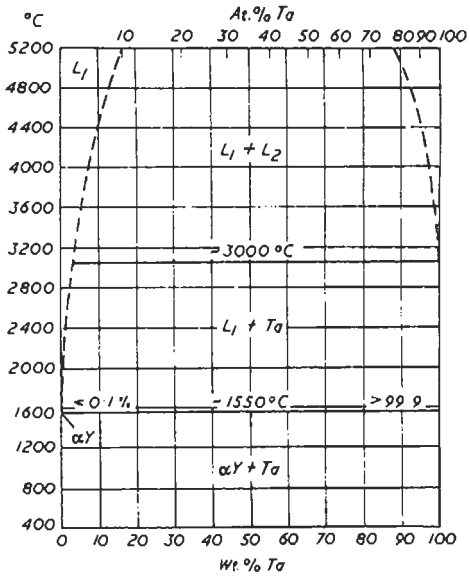
Ta–V


Wt. % V
°C
5
10
15
20
30
40
50
75
3200
3014°
2800
2400
2000
1600
1200
800
TaV2
Liquid
1926°
~1320°
0
10
20
30
40
50
60
70
80
90
100
At. % V

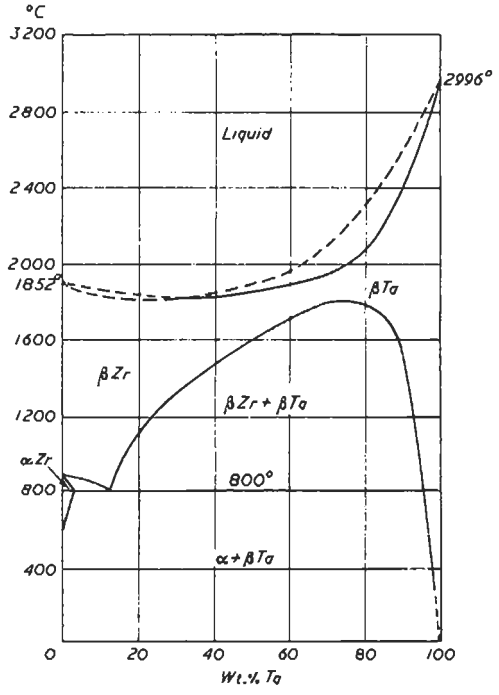
Ta–W


Wt. % W
°C
10
20
30
40
50
60
70
80
90
3600
3400
3200
3014°
3000
2800
Liquid
3423°
0
10
20
30
40
50
60
70
80
90
100
At. % W

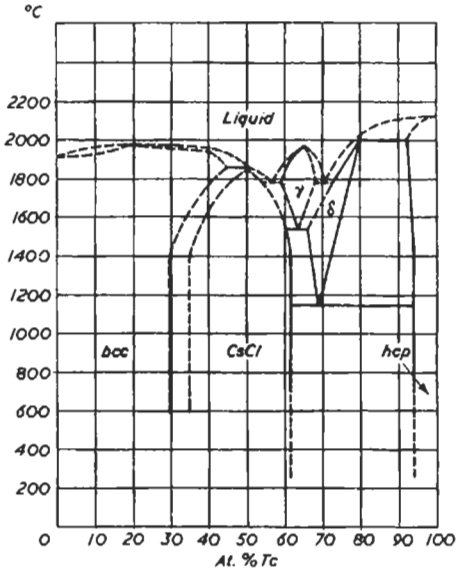
Ta–Y


°C
At.% Ta
10 20 30 40 50 60 70 80 90 100
5200
4800
4400
4000
3600
3200
2800
2400
2000
1600
1200
800
400
L_1
$L_1 + L_2$
≈3000 °C
$L_1 + Ta$
< 0·1 %
≈1550°C
> 99·9
αY
αY + Ta
0 10 20 30 40 50 60 70 80 90 100
Wt. % Ta

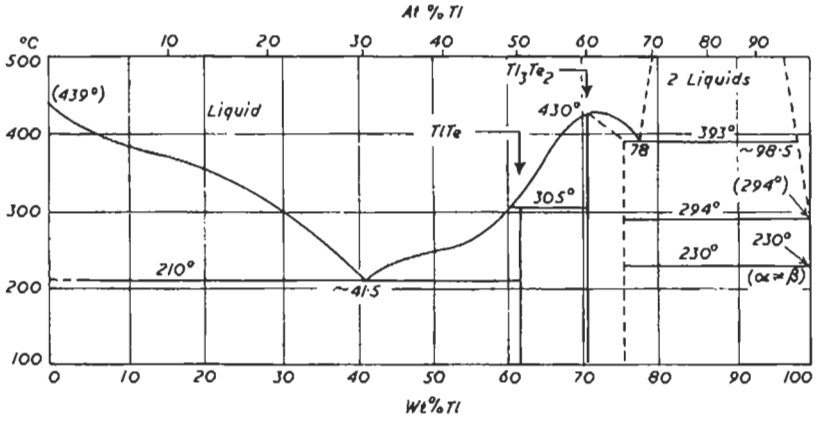
Ta–Zr


°C
3200
2800
2400
2000
1852°
1600
1200
800
400
2996°
Liquid
βTa
βZr
βZr + βTa
αZr
800°
α + βTa
0 20 40 60 80 100
Wt.% Ta

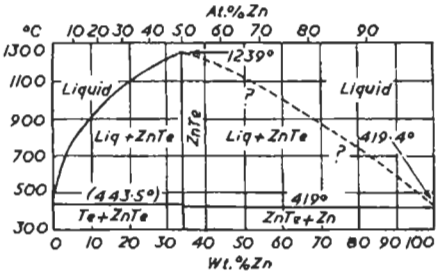
Tc–V



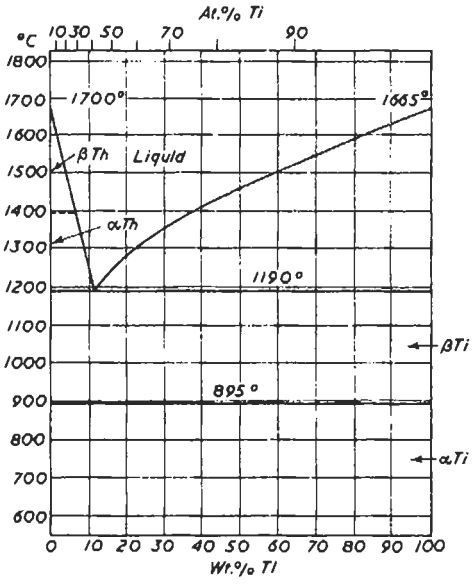
Te–Tl



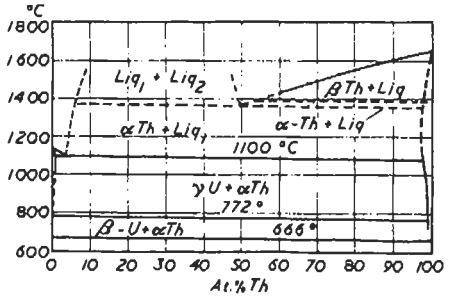
Te–Zn



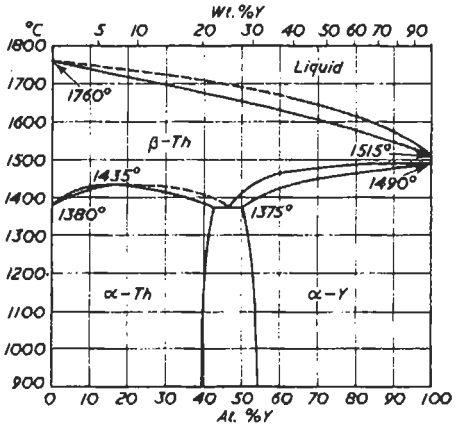
Th–Ti


At.% Ti
°C
1700°
1665°
βTh
Liquid
αTh
1190°
βTi
895°
αTi
Wt.% Ti

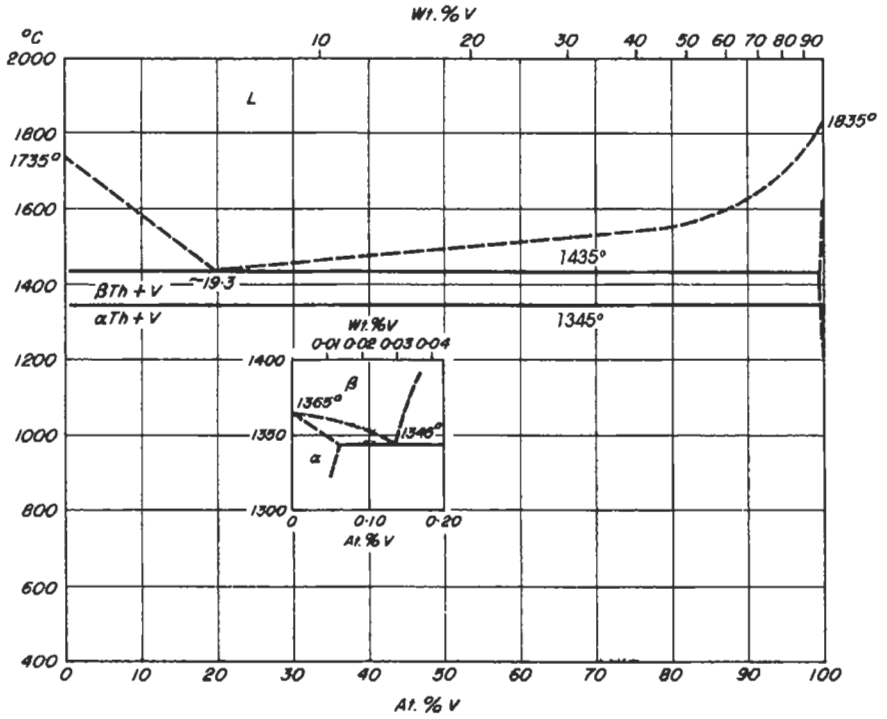
Th–U


°C
Liq1 + Liq2
βTh + Liq
αTh + Liq1
α-Th + Liq
1100 °C
γU + αTh
772°
β-U + αTh
666°
At.% Th

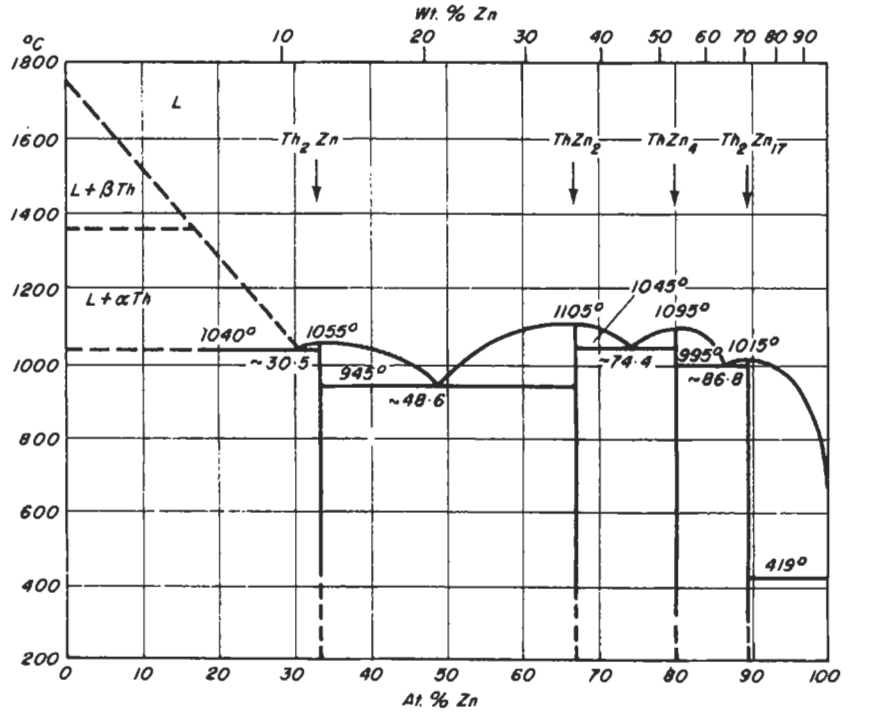
Th–Y


Wt.%Y
°C
Liquid
1760°
β-Th
1515°
1435°
1490°
1380°
1375°
α-Th
α-Y
At. %Y

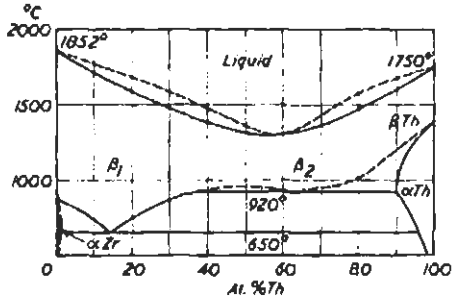
Th–V


Wt. % V
°C
L
1835°
1735°
1435°
~19·3
βTh + V
αTh + V
1345°
Wt. %V
0·01 0·02 0·03 0·04
β
1365°
1340°
α
At. % V
At. % V

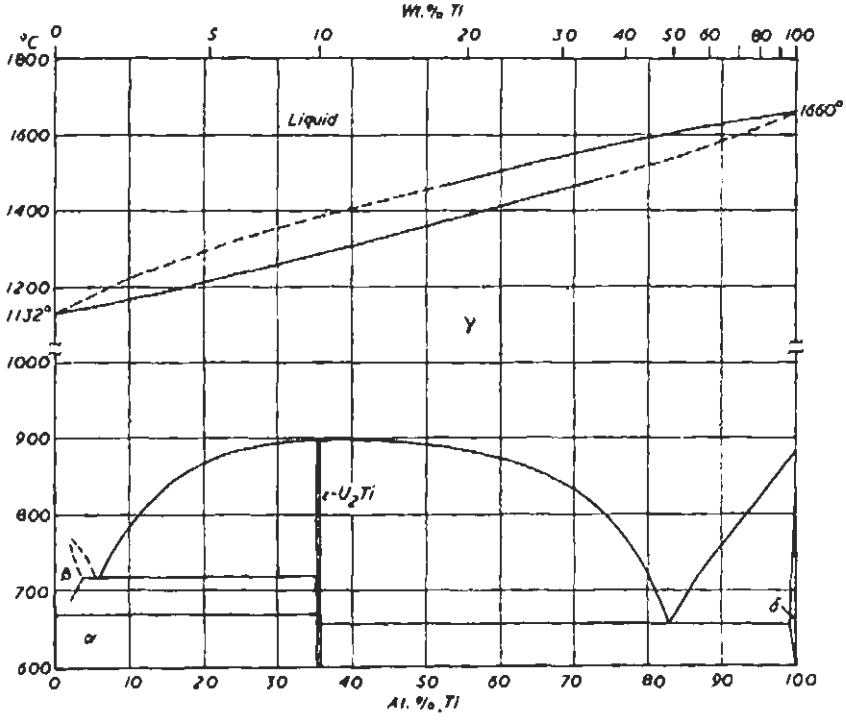
Th–Zn


Wt. % Zn
°C
L
Th2Zn
ThZn2
ThZn4
Th2Zn17
L + βTh
L + αTh
1040°
1055°
~30·5
945°
~48·6
1105°
1045°
1095°
~74·4
995°
1015°
~86·8
419°
At. % Zn

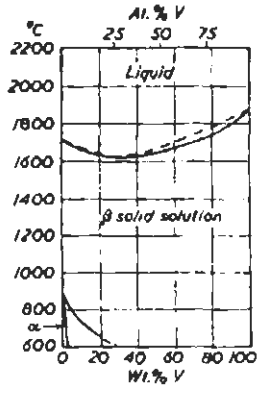
Th–Zr


°C
2000
1500
1000
1852°
Liquid
1750°
βTh
β1
β2
αTh
920°
650°
αZr
0
20
40
60
80
100
At. %Th

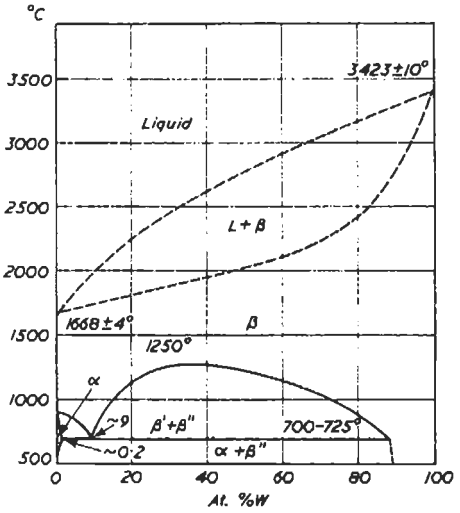
Ti–U


Wt. % Ti
°C
0
5
10
20
30
40
50
60
80
100
1800
1600
1400
1200
1132°
1000
900
800
700
600
Liquid
1660°
γ
ε-U2Ti
β
α
δ
0
10
20
30
40
50
60
70
80
90
100
At. % Ti

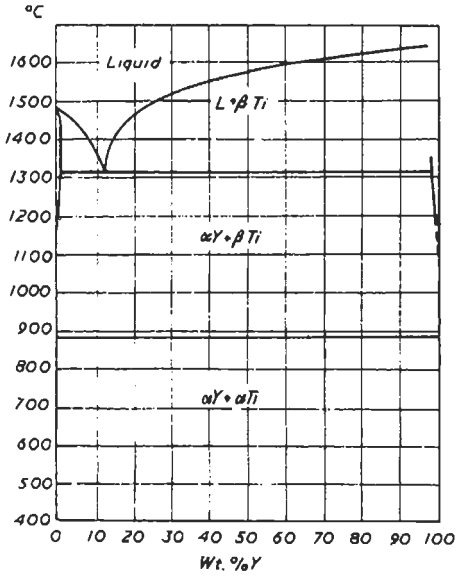
Ti–V


At. % V
°C
25
50
75
2200
2000
1800
1600
1400
1200
1000
800
600
Liquid
β solid solution
α
0
20
40
60
80
100
Wt. % V

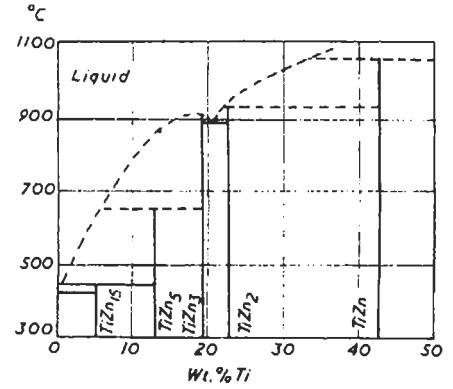
Ti–W


°C
3500
3000
2500
2000
1500
1000
500
3423±10°
Liquid
L+β
1668±4°
β
1250°
α
~9
β'+β"
700–725°
~0·2
α+β"
0
20
40
60
80
100
At. %W

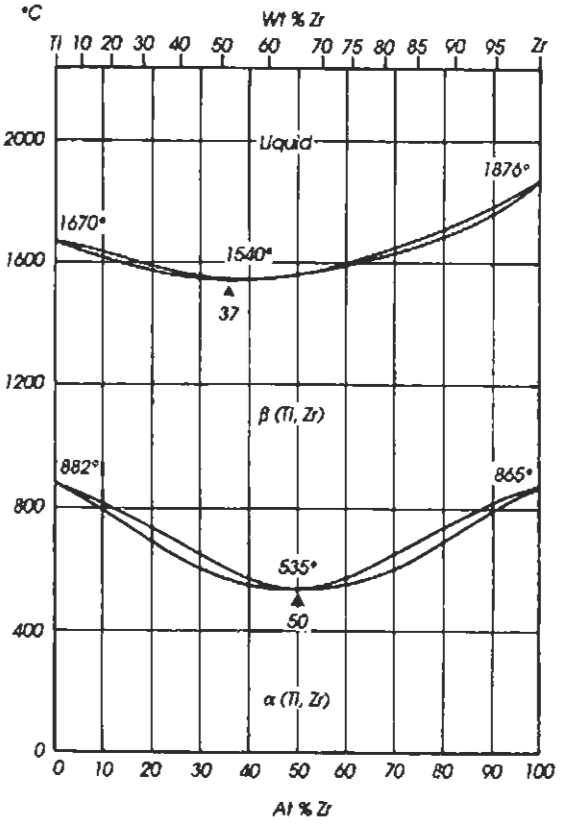
Ti–Y


°C
1600
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
Liquid
L+β Ti
αY+β Ti
αY+αTi
0
10
20
30
40
50
60
70
80
90
100
Wt. %Y

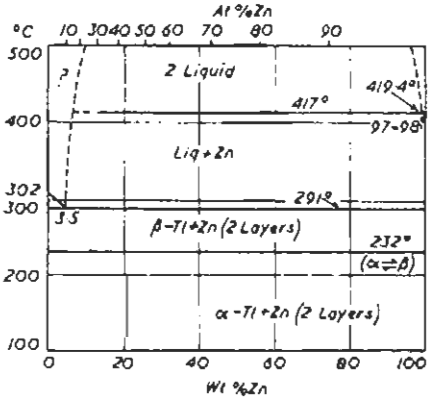
Ti–Zn


°C
1100
900
700
500
300
Liquid
TiZn15
TiZn5
TiZn3
TiZn2
TiZn
0
10
20
30
40
50
Wt. % Ti

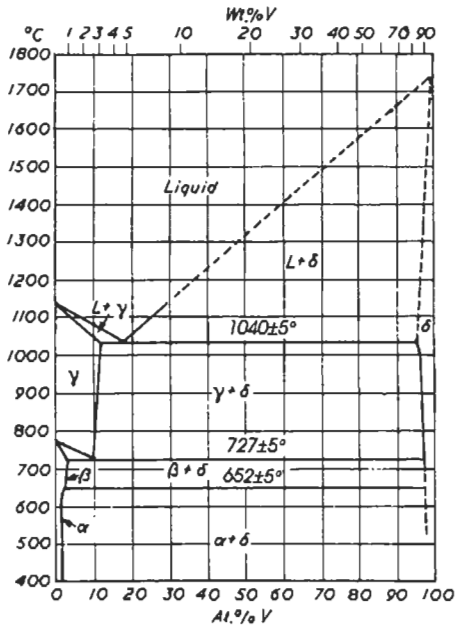
Ti–Zr


°C
Wt % Zr
Ti 10 20 30 40 50 60 70 75 80 85 90 95 Zr
2000
1600
1200
800
400
0
Liquid
1876°
1670°
1540°
37
β (Ti, Zr)
882°
865°
535°
50
α (Ti, Zr)
0 10 20 30 40 50 60 70 80 90 100
At % Zr

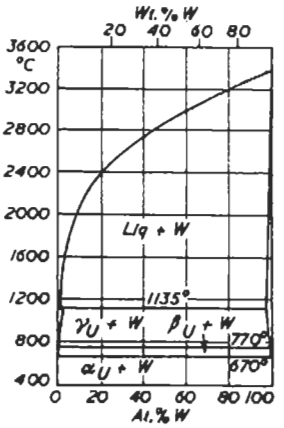
Ti–Zn


At %Zn
°C 10 3040 50 60 70 80 90
500
400
302
300
200
100
2 Liquid
419.4°
417°
97–98°
Liq + Zn
291°
β–Ti+Zn (2 Layers)
232°
(α⇌β)
α–Ti+Zn (2 Layers)
0 20 40 60 80 100
Wt %Zn

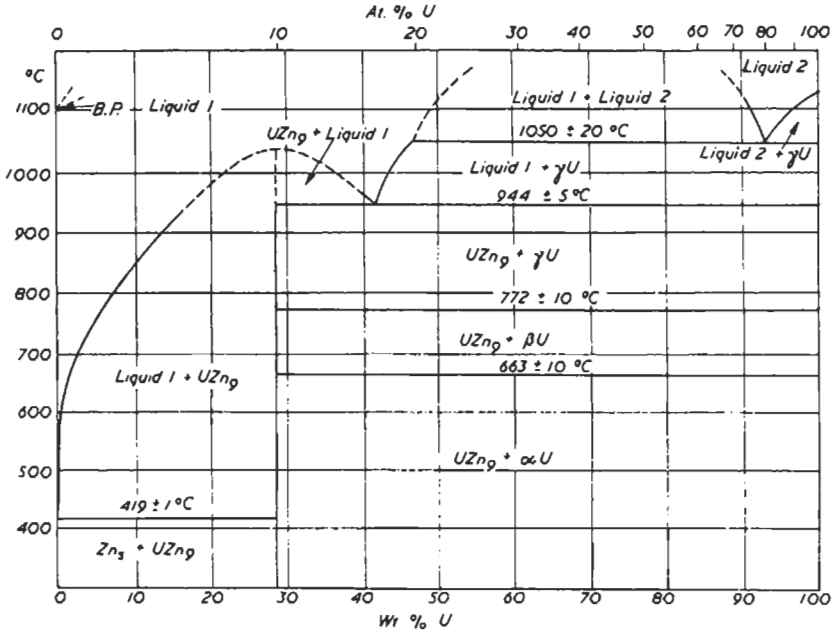
U–V



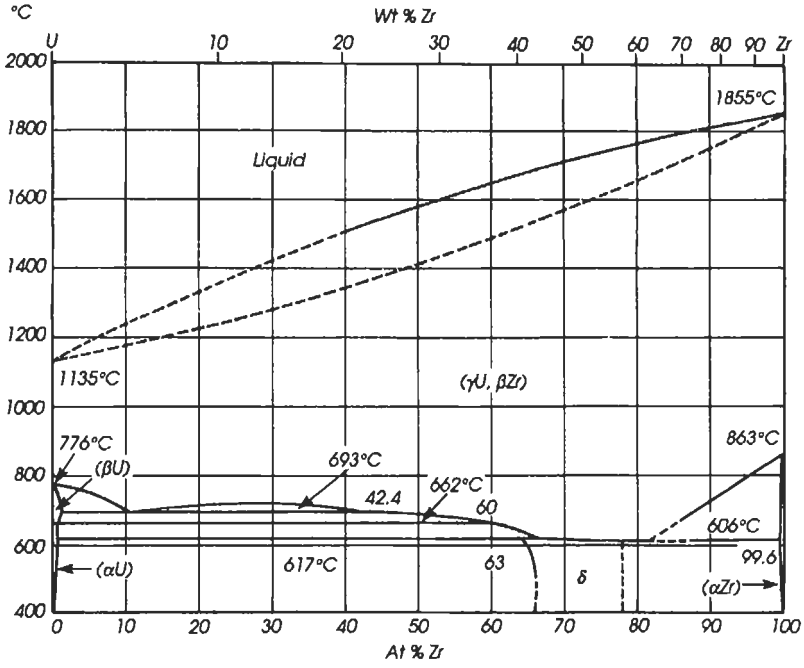
U–W



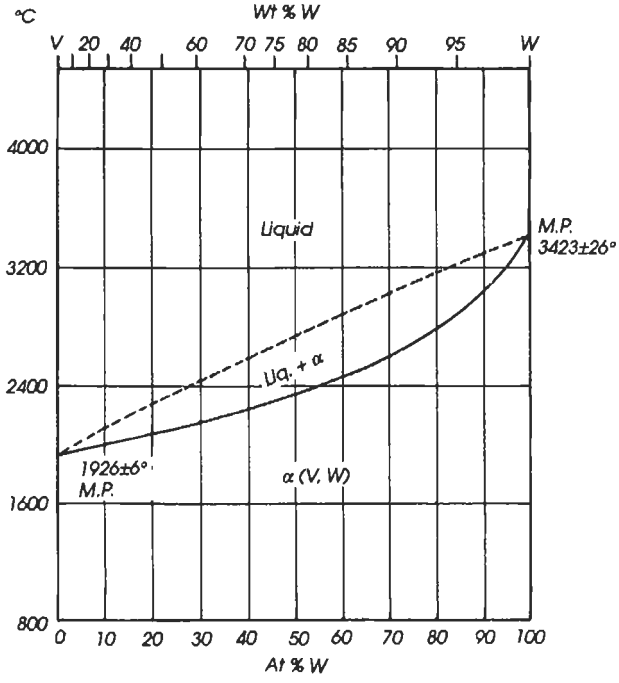
U–Zn at 5 atm



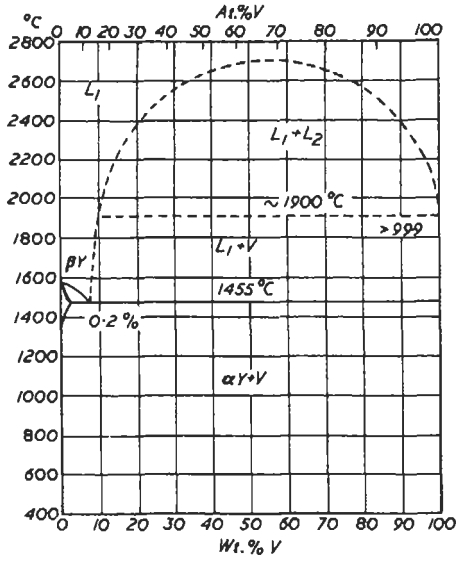
U–Zr


°C
Wt % Zr
U
10
20
30
40
50
60
70
80
90
Zr
2000
1800
1600
1400
1200
1000
800
600
400
1855°C
Liquid
1135°C
(γU, βZr)
776°C
(βU)
693°C
42.4
662°C
60
863°C
606°C
99.6
(αU)
617°C
63
δ
(αZr)
0
10
20
30
40
50
60
70
80
90
100
At % Zr

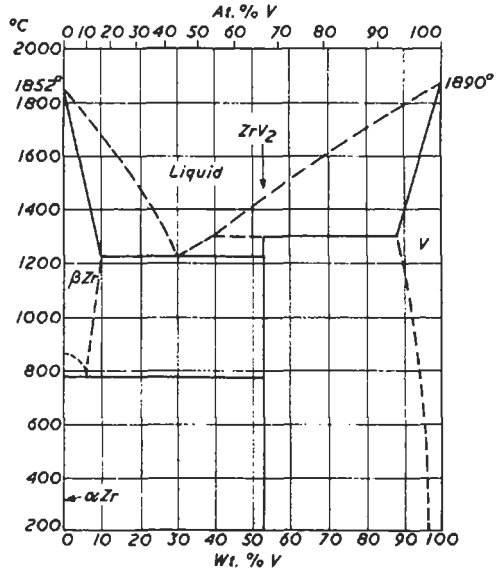
V–W


°C
Wt % W
V
20
40
60
70
75
80
85
90
95
W
4000
3200
2400
1600
800
Liquid
M.P.
3423±26°
Liq. + α
1926±6°
M.P.
α (V, W)
0
10
20
30
40
50
60
70
80
90
100
At % W

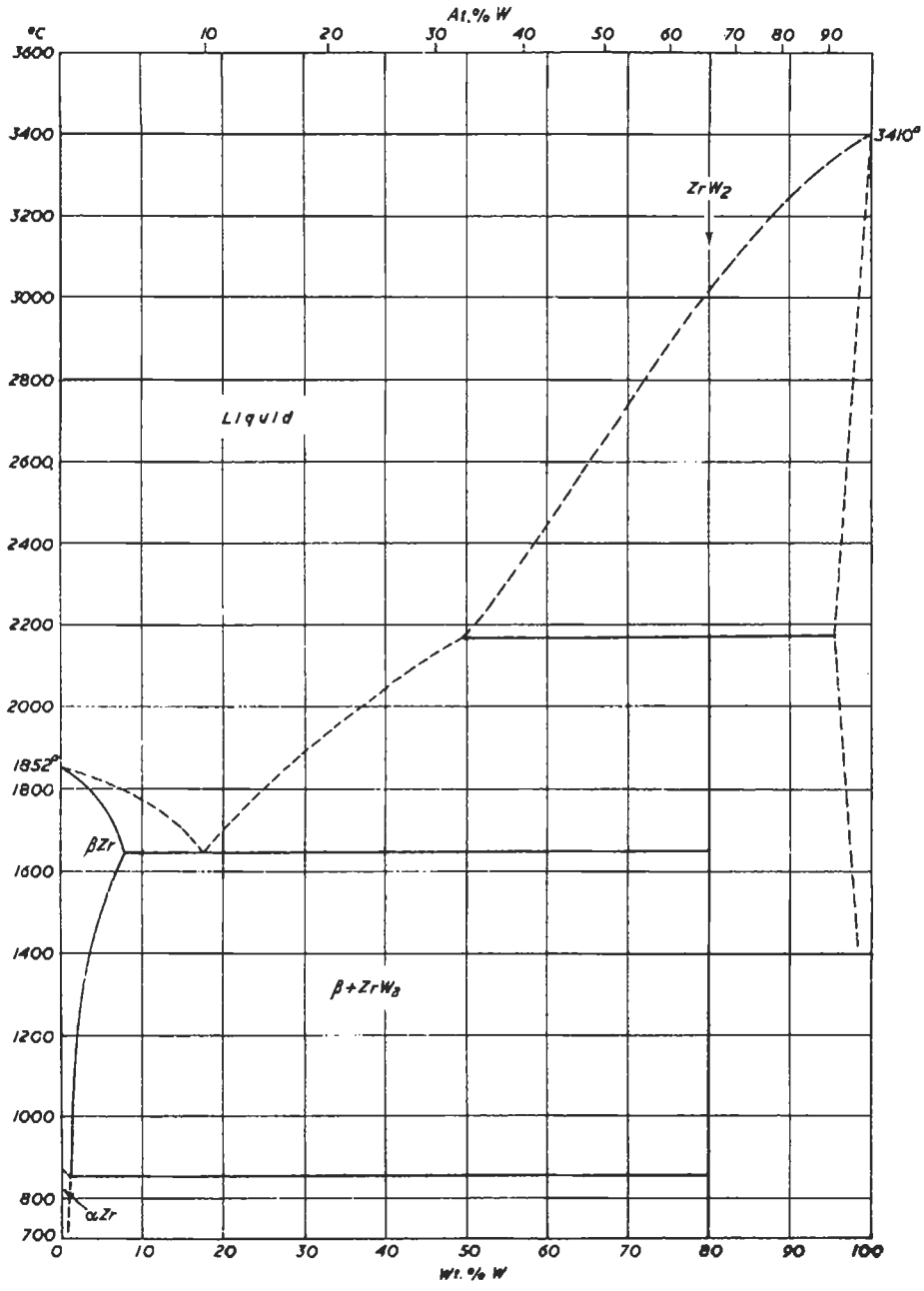
V–Y


°C
At.%V
0 10 20 30 40 50 60 70 80 90 100
2800
2600
2400
2200
2000
1800
1600
1400
1200
1000
800
600
400
L_1
L_1+L_2
≈ 1900 °C
> 999
L_1+V
βY
1455 °C
0·2 %
αY+V
0 10 20 30 40 50 60 70 80 90 100
Wt. % V

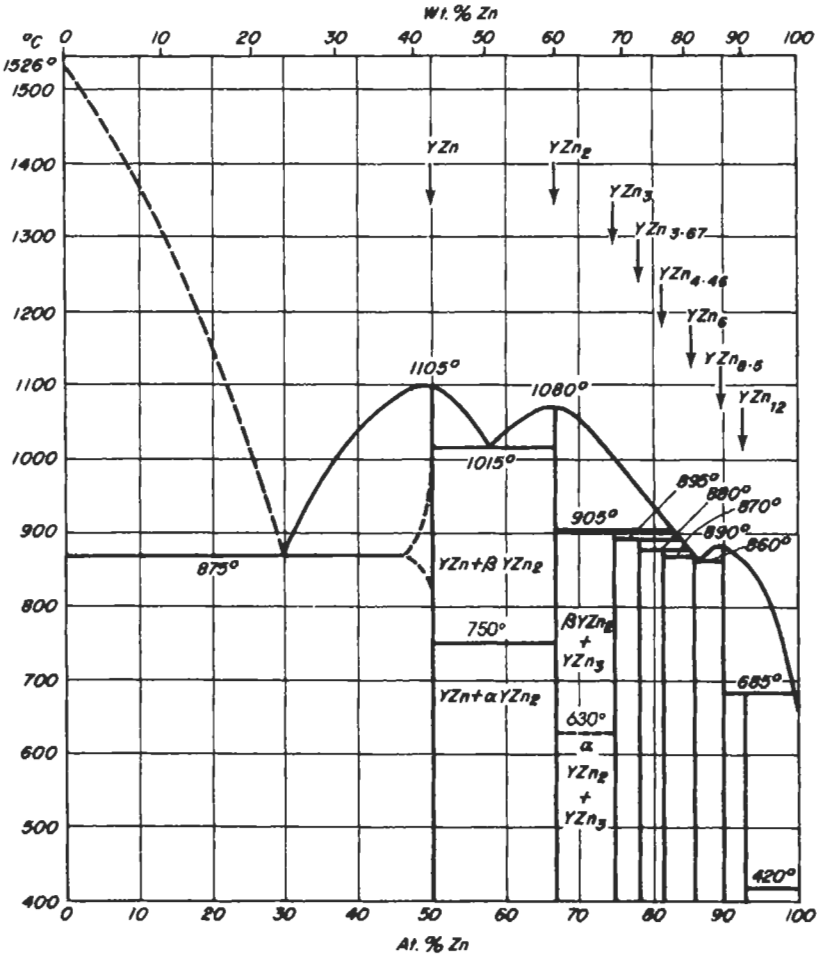
V–Zr


°C
At. % V
0 10 20 30 40 50 60 70 80 90 100
2000
1852°
1800
1600
1400
1200
1000
800
600
400
200
1890°
ZrV_2
Liquid
V
βZr
αZr
0 10 20 30 40 50 60 70 80 90 100
Wt. % V

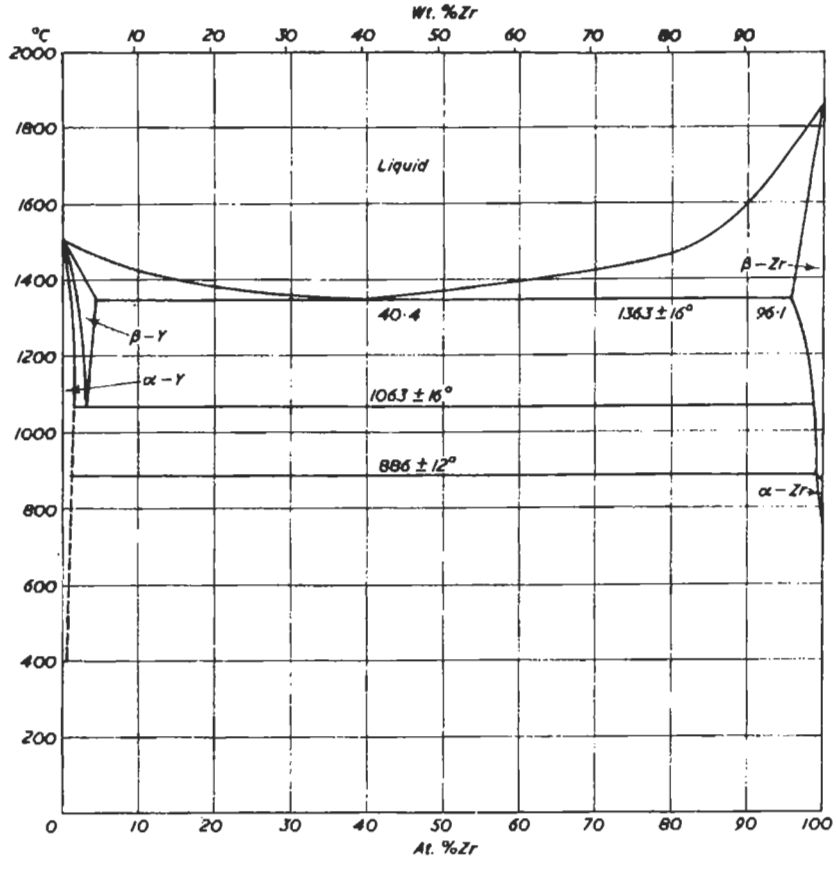
W–Zr


°C
At.% W
10
20
30
40
50
60
70
80
90
3600
3400
3200
3000
2800
2600
2400
2200
2000
1852°
1800
1600
1400
1200
1000
800
700
3410°
ZrW2
Liquid
βZr
β+ZrW2
αZr
0
10
20
30
40
50
60
70
80
90
100
Wt. % W

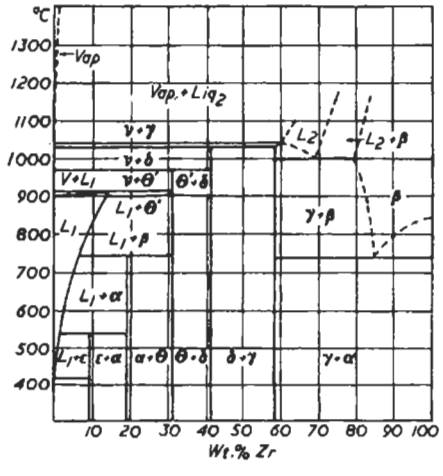
Y–Zn


Wt. % Zn
°C
0
10
20
30
40
50
60
70
80
90
100
1526°
1500
1400
1300
1200
1100
1000
900
800
700
600
500
400
YZn
YZn2
YZn3
YZn3·67
YZn4·46
YZn6
YZn8·6
YZn12
1105°
1080°
1015°
895°
880°
870°
890°
860°
905°
875°
YZn+β YZn2
750°
βYZn2 + YZn3
685°
YZn+α YZn2
630°
α YZn2 + YZn3
420°
At. % Zn

Y–Zr


Wt. %Zr
°C
10 20 30 40 50 60 70 80 90
2000
1800
1600
1400
1200
1000
800
600
400
200
0
Liquid
β – Zr
β – Y
α – Y
40·4
1363 ± 16°
96·1
1063 ± 16°
886 ± 12°
α – Zr
10 20 30 40 50 60 70 80 90 100
At. %Zr

Zn–Zr


°C
1300
1200
1100
1000
900
800
700
600
500
400
Vap
Vap. + Liq2
ν + γ
ν + δ
V + L1
ν + θ'
θ' + δ
L1 + θ'
L1 + β
L1
L1 + α
L1 + ε
ε + α
α + θ
θ + δ
δ + γ
γ + α
L2
L2 + β
γ + β
β
10 20 30 40 50 60 70 80 90 100
Wt.% Zr

11.3 Acknowledgements

The diagrams of the binary systems have been taken from the following sources and thanks are made to the publishers and authors concerned.

The source references are shown in '11.1 Index of binary diagrams' as a number in parenthesis. For those marked (8) see list below. Those without a number are from material taken from 'Constitution of Binary Alloys', M. Hansen and K. Anderko, McGraw-Hill, New York, 1958 and from the Supplements by R. P. Elliott, 1965 and by F. A. Shunk, 1969.

(1) 'Binary Alloy Phase Diagrams' or 'Bulletin of Alloy Phase Diagrams', Massalski, ASM, Metals Park, Ohio, 44073, U.S.A.

(2) 'Handbook of Binary Diagrams', W. G. Moffatt, Genium Publications Corp., N.Y.

(3) *J. of less-common Metals.* For references see 11.3.2 below.

(4) *International Atomic Energy*, Vienna.

(5) 'Phase Diagrams of Binary Gold Alloys', K. A. Gschneider *et al.*, 1987.

(6) 'Manganese Phase Diagrams', The Manganese Centre, Paris, France.

(7) 'Metals Handbook', ASM.

(8) See below—in 11.3.1.

11.3.1 Binary systems

Ag–Al	H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag. No.* 21.
Ag–As	Hansen; G. Eade and W. Hume-Rothery, *Z. Metallk.*, 1959, **50**, 123
Ag–Bi	Hansen; M. W. Nathans and M. Leider, *J. Phys. Chem.*, 1962, **66**, 2012
Ag–Ca	W. A. Alexander *et al.*, *Can. J. Chem.*, 1969, **47**, 611; A. N. Campbell and W. H. W. Wood, *Can. J. Chem.*, 1971, **49**, 1315
Ag–Cd	F. C. Kracek, 'Metals Handbook', Cleveland, Ohio, 1948
Ag–Dy	S. Delfino *et al.*, *J. less-common Metals*, 1976, **44**, 267
Ag–Ga	Hansen; W. Hume-Rothery and K. W. Andrews, *J. Inst. Metals*, 1942, **68**, 133; *Idem*, *Z. Metallk.*, 1959, **50**, 661
Ag–Gd	G. Kiessler *et al.*, *J. less-common Metals*, 1972, **26**, 293
Ag–Ge	Hansen; E. A. Owen and V. W. Rowlands, *J. Inst. Metals*, 1940, **66**, 371
Ag–Hg	H. M. Day and C. H. Mathewson, *Trans. Am. Min. Engrs*, 1938, **128**, 261
Ag–In	A. N. Campbell *et al.*, *Can. J. Chem.*, 1970, **48**, 1703
Ag–Li	W. G. Freeth and G. V. Raynor, *J. Inst. Metals*, 1953/4, **82**, 569
Ag–Mg	W. Hume-Rothery and K. W. Andrews, *J. Inst. Metals*, 1943, **69**, 488; G. F. Sager and B. J. Nelson, 'Metals Handbook', Cleveland, Ohio, 1948; J. L. Haughton and R. J. M. Payne, *J. Inst. Metals*, 1937, **60**, 351
Ag–Mn	R. Hultgren *et al.*, 'Selected Values of the Thermodynamic Props. of Binary Alloys', American Society for Metals, 1973
Ag–Na	Hansen; J. R. Weeks, *Trans. Quart. ASM*, 1969, **62**, 304
Ag–P	R. Vogel *et al.*, *Z. Metallk.*, 1959, **50**, 130
Ag–Sb	Hansen; P. W. Reynolds and W. Hume-Rothery, *J. Inst. Metals*, 1937, **60**, 365
Ag–Sc	I. Stapf *et al.*, *J. less-common Metals*, 1975, **39**(2), 219
Ag–Sn	Equilibrium Data for Sn Alloys, *Tin Res. Inst.*, 1949
Ag–Sr	F. Weibke, *Z. Anorg, Chem.*, 1930, **193**, 297; T. Heumann and N. Harmsen, *Z. Metallk.*, 1970, **61**, 906
Ag–Tb	S. Delfino *et al.*, *Z. Metallk.*, 1976, **67**(6), 392
Ag–Th	E. Raub, *Z. Metallk.*, 1949, **40**, 431
Ag–Ti	M. K. McQuillan, *J. Inst. Metals.*, 1959/60, **88**, 235
Ag–Tl	E. Raub, *Z. Metallk.*, 1949, **40**, 432
Ag–U	R. W. Buzzard *et al.*, *J. Res. natn. Bur. Stand.*, 1954, **52**, 149
Ag–Yb	A. Palenzona, *J. less-common Metals*, 1970, **21**, 443
Ag–Zn	W. Hume-Rothery *et al.*, *Proc. Roy. Soc.*, 1941, **A 177**, 149
Ag–Zr	J. O. Betterton and D. S. Easton, *Trans. Am. Inst. Min. Engrs*, 1958, **12**, 470
Al–As	W. Köster and B. Thoma, *Z. Metallk.*, 1955, **46**, 291
Al–Be	H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag. No.* 19
Al–Bi	R. Martin-Garin *et al.*, *Compte Rendu*, [C], 1966, **262**, 335
Al–Ce	K. H. J. Buschow and J. H. N. van Vucht, *Z. Metallk.*, 1966, **57**, 162
Al–Co	H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag. No.* 20
Al–Cr	G. Falkenhagen and W. Hofmann, *Z. Metallk.*, 1950, **41**, 191

Al–Cs V. D. Bushmanov and S. P. Yatsenko, *Russ. Met.* (*Metally*), 1981, 5

Al–Cu G. V. Raynor, *Inst. Met. Ann. Eq. Diag. No.* 4; R. P. Jewitt and D. J. Mack, *J. Inst. Met.*, 1963/4, **92**, 59

Al–Dy F. Casteels, *J. less-common Metals*, 1967, **12**, 210

Al–Er K. H. J. Buschow and J. H. N. van Vucht, *Z. Metallk.*, 1965, **56**, 9

Al–Fe H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag., No.* 13

Al–Gd K. H. J. Buschow, *J. less-common Metals*, 1965, **9**, 453.

Al–Hf E. M. Savitskii *et al.*, *Russ. Met.*, 1970, (1), 107

Al–In B. Predel, *Z. Metallk.*, 1965, **56**, 791

Al–La K. H. J. Buschow, *Philips Res. Reports*, 1965, **20**, 337.

Al–Mn T. Godecke and W. Köster, *Z. Metallk.*, 1971, **62**(1), 727

Al–Nb C. E. Lundin and A. S. Yamamoto, *Trans. Am. Inst. Min. Engrs*, 1966, **236**, 863

Al–Nd K. H. J. Buschow, *J. less-common Metals*, 1965, **9**, 452

Al–Ni W. O. Alexander and N. B. Vaughan, *J. Inst. Metals*, 1937, **61**, 250; H. Groeber and V. Hauk, *Z. Metallk.*, 1950, **41**, 283; H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag. No.* 18

Al–Pb E. Scheil and E. Jahn, *Z. Metallk.*, 1949, **40**, 319

Al–Pr K. H. J. Buschow and J. H. N. van Vucht, *Z. Metallk.*, 1966, **57**, 162

Al–Pt R. Huch and W. Klemm, *Z. anorg. allg. Chem.*, 1964, **329**, 123

Al–Pu F. H. Ellinger *et al.*, *J. nucl. Mater.*, 1962, **5**, 165

Al–Ru W. Obrowski, *Metall*, 1963, **17**, 108

Al–Sb H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag. No.* 15

Al–Sc O. P. Naumkin *et al.*, *Metally Splavŷ Élektrotekh.*, 1965, (4), 176

Al–Si H. W. L. Phillips, *Inst. Met. Ann. Eq. Diag. No.* 16

Al–Sm F. Casteels, *J. less-common Metals*, 1967, **12**, 210

Al–Sn R. C. Dorward, *Metal Trans. A*, 1976, **7A**(2), 308

Al–Sr B. Closset *et al.*, *Metal Trans. A*, 1986, **17A**, 1250

Al–Th J. R. Murray, *J. Inst. Metals*, 1958/9, **87**, 349

Al–U P. R. Roy, *J. Nuc. Mat.*, 1964, **11**(1), 59

Al–V R. Flükiger *et al.*, *J. less-common Metals*, 1975, **40**(1), 103

Al–W W. D. Clark, *J. Inst. Metals*, 1940, **66**, 271.

Al–Yb A. Palenzona, *J. less-common Metals*, 1972, **29**, 289

Al–Zn G. V. Raynor, *Inst. Met. Ann. Diag. No.* 1; G. R. Goldak and J. G. Parr, *J. Inst. Met.*, 1963/4, **92**, 230

Al–Zr W. L. Fink and L. A. Wiley, *Trans. Am. Inst. Min. Engrs*, 1939, **133**, 69; D. J. McPherson and M. Hansen, *Trans. Am. Soc. Metals*, 1954, **46**, 354

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Cr–Nb 1961, **3** (1), 44
Cs–In 1982, **83**, 143
Cu–Eu 1985, **106**, 175
Cu–Gd 1983, **92**, 143
Cu–Nd 1983, **92**, 97
Er–In 1983, **90**, 95
Ga–Tm 1979, **64**, 185
Gd–In 1983, **90**, 95
Gd–Pd 1973, **30**, 47
Ge–Ni 1980, **72**, 51
In–La 1974, **38**, 13
In–Nd 1983, **90**, 95
In–Y 1983, **90**, 95
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11.4 Ternary systems and higher systems

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12 Gas–metal systems

12.1 The solution of gases in metals

The gases which can be found in solution in measurable quantities in metals are the diatomic gases hydrogen, nitrogen and oxygen and also the noble gases in Group 8 of the Periodic Table.

12.1.1 Dilute solutions of diatomic gases

A diatomic gas dissociates on solution so that equilibrium between the solute and the gas phase is written:

$$X_2 \text{ (gas)} \rightleftharpoons 2X \text{ (dissolved in metal)}$$

In systems where no gas–metal compounds are formed and where also the solute does not contribute to the stability of the metallic phase, solutions are usually so dilute that Henry's law applies. If, also, the ideal gas laws are assumed for the gas phase and the standard states selected are (1) the infinitely dilute atomic fraction for the solute and (2) the pure element at a standard pressure $p^\ominus$ for the gas, the equilibrium constant is given by:

$$K = \frac{a_x^2}{a_{x_2}} = \frac{N_x^2 p^\ominus}{p} \tag{12.1}$$

where a_x and a_{x_2} are the activities of the solute and the diatomic gas, N_x is the atomic fraction of solute and p is the pressure of the gas. In a form rearranged to express the proportionality between the solute concentration, C, and the square root of the gas pressure, p, equation (12.1) is known as Sievert's relation:

$$C = S\left(\frac{p}{p^\ominus}\right)^{1/2} \tag{12.2}$$

where S is the solute concentration in equilibrium with the standard pressure, $p^\ominus$.

Values for solubilities in dilute solutions are usually presented as solute concentrations in equilibrium with the pure gas at one atmosphere pressure (101 325 Pa). The units of concentration in common use are cm^3 of gas measured at one atmosphere pressure and 273 K per 100 g of metal for hydrogen and mass % for nitrogen and oxygen.

Application of the Van't Hoff isochore gives the variation with temperature of the equilibrium constant at constant pressure and hence also of the corresponding equilibrium solute concentration:

$$\left(\frac{\mathrm{d}\ln K}{\mathrm{d}T}\right)_p = \frac{\Delta H^\ominus}{RT^2}$$

where $H^\ominus$ is the standard enthalpy of solution of the gas. Substituting for K from equation (12.1) gives:

$$\left(\frac{\mathrm{d}\ln N_x}{\mathrm{d}T}\right)_p = \frac{\Delta H^\ominus}{2RT^2}$$

For a small range of temperature it is permissible to disregard the temperature-dependence of ΔH° so that integration then yields:

$$\log\left(\frac{N_1}{N_2}\right)=\frac{-\Delta H^\circ}{2.303\times 2R}\left(\frac{1}{T_1}-\frac{1}{T_2}\right) \tag{12.3}$$

where N_1 and N_2 are the atomic fractions of solute in equilibrium at temperatures T_1 and T_2 with the same gas pressure. Standard enthalpies of solution ΔH° can be evaluated from experimental results fitted to equation (12.3), bearing in mind Kubaschewski's reminder[1] that thermochemical data derived from the temperature-dependence of equilibrium constants are uncertain.

12.1.2 Complex gas–metal systems

In systems where the solute contributes to the stability of the metallic phase or where near stoichiometric compounds separate, the information of interest extends to high solute concentrations where there is deviation from Henry's law and to equilibria between condensed phases. If complete, this information is most conveniently presented graphically as isotherms, i.e. expressing composition as a function of equilibrium pressure for selected temperatures. Regions where two condensed phases coexist in the system are manifest by pressure invariance between the compositions of the conjugate phases. For some systems, the available experimental results are limited to values for solute concentrations in equilibrium at selected temperatures with either a second phase or the gas at a selected pressure.

12.1.3 Solutions of hydrogen

Table 12.1 gives selected values of dissolved hydrogen concentrations in equilibrium with hydrogen at one atmosphere pressure for the metals silver, aluminium, cobalt, chromium, copper, iron, magnesium, manganese, molybdenum, nickel, lead, platinum, silicon, tin, zinc and some of their alloys. The solutions are dilute and form endothermically from the gas phase, so that the solubility of hydrogen increases with temperature (except for α-manganese).

The alkali and alkaline-earth metals form hydrides with non-metallic characteristics in which bonding is of predominantly ionic character with the hydrogen present as H^- anions. Table 12.2 gives hydrogen concentrations in equilibrium with the corresponding hydrides for barium, calcium, magnesium, sodium and strontium.

Certain of the metals in the transition, rare earth and actinide series have the remarkable ability to take hydrogen into interstitial solid solution until the atomic fraction of hydrogen approaches simple stoichiometric ratios but without loss of the metallic character of the phase so formed. Additional phases may also appear at higher hydrogen concentrations. The solute hydrogen increases the stability of the metallic phase, the solution process is exothermic and thus for a given hydrogen activity (i.e. for constant pressure of hydrogen in the gas phase) the stability decreases with temperature. Figures 12.1 to 12.11 present information for the systems formed by hydrogen with cerium, niobium, neodymium, palladium, praseodymium, plutonium, tantalum, thorium, titanium, vanadium and zirconium. Tables 12.3 and 12.4 give data for uranium and hafnium.

Table 12.1 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS HYDROGEN AT ATMOSPHERIC PRESSURE

Solvent metal	*Hydrogen concentration, S at T °C* cm³ *of gas at atmosphere pressure and* 0 °C *per* 100 g *of metal*							*References*
Ag	*T* 400	500	600	700	800	900	960.5	16
(solid)	*S* 0.056	0.11	0.18	0.23	0.33	0.43	0.52	
Al	*T* 350	400	500	600	660			18
(solid)	*S* 0.001 2	0.002 8	0.011	0.030	0.050			also 17
(liquid)	*T* 660	700	750	800	900	1 000		17, 19
	S 0.69	0.92	1.23	1.67	2.75	4.15		also 18

Table 12.1 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS HYDROGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal			*Hydrogen concentration, S at T °C* cm³ *of gas at atmospheric pressure and 0 °C per 100 g of metal*									*References*
Al–Cu	*T*		700	800	900	1 000						
(liquid)	*S*	2% Cu	0.75	1.35	2.45	3.80						19
		4% Cu	0.65	1.15	2.25	3.45						19
		8% Cu	0.50	0.95	1.85	2.95						19
		16% Cu	0.40	0.80	1.35	2.30						19
		32% Cu	0.35	0.65	1.15	1.80						19
Al–Si	*T*		700	800	900	1 000						
(liquid)	*S*	2% Si	0.75	1.50	2.50	3.90						19
		4% Si	0.70	1.35	2.35	3.75						19
		8% Si	0.60	1.25	2.25	3.60						19
		16% Si	0.50	1.23	2.15	2.37						19
Co	*T*	600	700	800	900	1 000	1 100	1 200	1 300	1 400	1 492	
(solid)	*S*	0.9	1.22	1.85	2.51	3.30	4.31	5.40	6.7	7.75	8.65	20, 21
(liquid)	*T*	1 500	1 550	1 600	1 650							
	S	20.5	21.6	23.2	24.3							21, 22
Co–Fe	*See* Fe–Co											
Co–Ni	*See* Ni–Co											
Cr	*T*	400	500	600	700	800	900	1 000	1 100	1 200		24
(solid)	*S*	0.2	0.3	0.4	0.6	1.0	1.7	2.6	3.7	5.4		also 23
Cr–Fe	*See* Fe–Cr											
Cu	*T*	300	400	500	600	700	800	900	1 000	1 083		25, 27
(solid)	*S*	0.01	0.05	0.11	0.21	0.27	0.53	0.89	1.34	1.9		also 21, 26
(liquid)	*T*	1 083	1 100	1 150	1 200	1 250	1 300	1 350	1 400			27
	S	5.1	5.4	6.3	7.2	8.3	9.2	10.4	11.8			also 21, 26, 28
Cu–Ag	*T*		1 225	1 225	1 225	1 225	1 225					
(liquid)	% Ag		0	10	20	30	50					
	S		8.6	7.9	7.0	5.9	4.3					7
Cu–Al	*T*		700	800	900	1 000	1 050					
(solid)	*S*	1.43% Al	—	—	0.70	1.15	1.40					27
		3.3% Al	—	0.35	0.70	1.05	1.25					27
		5.77% Al	—	0.10	0.30	0.60	—					27
		6.84% Al	0.10	0.15	0.35	0.65	—					27
		8.1% Al	0.10	0.15	0.35	0.75	—					27
Cu–Al	*T*		1 100	1 150	1 200	1 300	1 400					
(liquid)	*S*	1.45% Al	5.1	5.8	6.6	—	—					27
		3.3% Al	4.4	5.1	5.7	—	—					27
		5.77% Al	3.3	3.9	4.5	—	—					27
		6.84% Al	3.0	3.5	4.1	—	—					27
		8.1% Al	2.7	3.2	3.5	4.5	5.9					27 also 7
Cu–Au	*T*		1 225	1 225	1 225	1 225						
(liquid)		% Au	0	10	30	50						
	S		8.6	7.9	5.6	3.4						7
Cu–Ni	*T*		1 225	1 225	1 225							
(liquid)		% Ni	0	10	20	*See also* Ni–Cu						
	S		8.6	13	17							7
Cu–Pt	*T*		1 225	1 225	1 225							
(liquid)		% Pt	0	10	20							
	S		8.6	9.6	9.7							7

Table 12.1 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS HYDROGEN AT ATMOSPHERIC PRESSURE *–continued*

Solvent metal			*Hydrogen concentration, S at T °C* cm³ *of gas at atmospheric pressure and* 0 °C *per* 100 g *of metal*										*References*
Cu–Sn	*T*		1 000	1 100	1 200	1 300							
(liquid)	*S*	5.9% Sn	—	4.80	6.28	7.81							28
		11.5% Sn	3.09	4.11	5.35	6.85							28
		21.7% Sn	2.11	2.97	3.94	5.10							28
		40.2% Sn	0.53	0.94	1.50	—							28
		54.8% Sn	0.50	0.76	1.15	1.61							28
													also 7
Cu–Zn	*T*		500	600	700	800	875*						
(solid α)	*S*	33% Zn	0.010	0.023	0.044	0.076	0.35						29
			(* α+β region)										
Fe	*T*		200	300	400	500	600	700	800	900			24
(solid α)	*S*		—	0.1	0.2	0.6	1.2	1.7	2.4	3.0			also 30, 31, 32
	T		900	1 000	1 100	1 200	1 250	1 350	1 400				24
(solid γ)	*S*		4.7	5.4	6.4	7.4	8.4	—	9.3				also 21, 31, 33
Fe	*T*		1 400	1 450									24
(solid δ)	*S*		6.1	6.4									also 21, 31, 33
(liquid)	*T*		1 535	1 550	1 600	1 700							59, 60, 61
	S		24.5	25.5	26.5	29.5							21
													also 22, 31, 33
													34, 35, 36
Fe–Co	*T*		1 600	1 600	1 600	1 600	1 600						
(liquid)		% Co	0	20	40	60	80						
	S		29.8	23.8	20.7	18.2	21.5						22
Fe–Cr	*T*		400	600	700	800	850	900	1 000	1 100	1 200		
(solid)	*S*	4% Cr	0.2	0.9	1.4	1.9	2.2	4.4	5.3	6.3	7.4		24
		10% Cr	0.2	0.7	1.2	2.1	5.0	6.0	7.1	8.3	9.3		24
		20% Cr	0.2	0.5	1.8	3.0	3.7	4.3	4.9	5.6	6.6		24
		44% Cr	0.2	0.5	1.2	2.3	3.5	4.3	5.4	6.2	6.9		24
		77% Cr	0.2	0.5	0.8	1.2	1.5	2.0	3.1	4.4	5.9		24
													also 33
Fe–Cr	*T*		1 600	1 600	1 600	1 600	1 600						
(liquid)		% Cr	9.4	18.8	28.5	38.3	48.2						
	S		25	25	25	24	23						33
Fe–Nb	*T*		1 560	1 685									
(liquid)	*S*	*5.01% Nb	24.6	28.3									36
		8.97% Nb	29.2	31.7									36
		15.12% Nb	41.7	43.8									36
			*Estimates from results for equilibrium at 2 900 Pa										
Fe–Ni	*T*		300	400	500	600	700	800	900	1 000	1 100	1 200	
(solid)	*S*	3.3% Ni	—	0.3	0.7	1.3	2.0	3.9	5.0	6.2	7.3	8.4	24
		5.5% Ni	0.2	0.4	0.8	1.4	2.1	4.1	5.2	6.3	7.3	8.4	24
		11.6% Ni	0.4	0.6	1.3	2.1	3.2	4.3	5.3	6.4	7.5	8.5	24
		21.0% Ni	0.5	0.7	1.4	2.2	3.3	4.3	5.4	6.5	7.6	8.8	24
		32.1% Ni	0.6	0.9	1.5	2.4	3.3	4.4	5.5	6.7	7.8	9.0	24
		53.2% Ni	0.8	1.2	1.8	2.7	3.7	4.7	5.8	6.9	8.1	9.3	24
		62.4% Ni	1.3	1.7	2.4	3.3	4.1	5.0	6.1	7.3	8.4	9.6	24
		72.4% Ni	1.6	1.8	2.6	3.4	4.3	5.2	6.3	7.4	8.7	9.9	24
		84.8% Ni	1.8	2.2	2.7	3.7	4.8	6.3	7.6	9.2	10.7	12.4	24
													also 21, 33
(liquid)	*T*		1 550	1 600	1 700								
	S	20% Ni	26.5	27.5	31								21
		40% Ni	28.5	30	32.5								21
		60% Ni	31.5	33	36								21
		80% Ni	36	38	41								21
													also 22, 33

Table 12.1 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS HYDROGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal		*Hydrogen concentration, S at T °C* cm³ *of gas at atmospheric pressure and 0 °C per 100 g of metal*									*References*
Fe Si	*T*	1 350	1 400	1 500	1 550	1 650					
(liquid)	*S* 1.78% Si	—	—	25.5	27.5	31.6					35
	11.0% Si	11.5	12.5	14.4	15.4	17.4					35
	21.7% Si	7.0	7.6	8.9	9.5	10.7					35
	31.5% Si	—	6.0	6.5	6.8	7.3					35
	39.1% Si	—	7.0	8.5	9.1	10.3					35
	45.7% Si	9.3	9.9	11.1	11.8	13.1					35
	51.5% Si	12.7	13.1	14.0	14.4	15.3					35
	63.7% Si	20.9	21.4	22.4	22.9	23.8					35
Fe–Ti	*T*	1 560	1 685								
(liquid)	*S* *0.18% Ti	24.3	26.7								36
	0.45% Ti	25.6	26.2								36
	0.70% Ti	28.2	30.6								36
	2.67% Ti	—	45.8								36
	3.14% Ti	50.0	52.9								36
		*Estimated from results for equilibrium at 2 900 Pa									
Fe–Cr–Ni	*T*	400	500	600	700	800	900	1 000	1 100	1 200	
(solid)	*S* 17.5% Cr + 9% Ni	0.2	0.8	1.8	2.4	3.4	4.9	6.4	7.7	8.8	24
	4.6% Cr + 10% Ni	0.6	1.0	1.7	2.8	3.6	4.4	5.5	6.6	8.1	24
Mg	*T*	650									
(solid)	*S*	15–30 (results unreliable)									38, 39, 41
(liquid)	*T*	675	725	775							41
	S	46	60	63	(results unreliable)						also 38, 39, 40
Mn	*T*	25	100	200	300	400	500	600	Marked hysteresis during		43
(solid α)	*S*	21.6	19.9	17.2	14.5	12.4	11.4	11.4	transition in range $600 < T < 800$		also 42
(solid β and γ)	*T*	800	850	900	950	1 000	1 050	1 100	1 125	Hysteresis during transition in range $1\,125 < T < 1\,150$	43
	S	28.6	29.3	30.1	31.4	32.8	34.2	40.0	42.2		also 42
Mn	*T*	1 150	1 175	1 200	1 225	1 243					
(solid δ)	*S*	41.1	41.7	42.8	44.4	46.6					43 also 42
(liquid)	*T*	1 243	1 250	1 275	1 300						
	S	46.6	50.0	58.3	60.2						43 also 42
Mo	*T*	500	600	700	800	900	1 000	1 100	1 200		
(solid)	*S*	0.8	1.3	1.7	2.2	1.8	1.2	0.8	0.5		23
Ni	*T*	300	400	500	600	700	800	900			
(solid)	*S*	2.0	2.5	3.3	4.3	5.6	7.0	8.5			21, 24 also 26, 32, 33
	T	1 000	1 100	1 200	1 300	1 400	1 453				
	S	10.0	11.5	13.0	14.0	16.5	18				21, 24 also 26, 32, 33
(liquid)	*T*	1 453	1 500	1 600	1 700						
	S	41	43	48	51						21 also 22, 26, 33, 34

Table 12.1 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS HYDROGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal			*Hydrogen concentration, S at T °C* cm³ *of gas at atmospheric pressure and 0 °C per 100 g of metal*											*References*
Ni–Co (solid)	*T*		1 400	1 400	1 400	1 400								
		% Co	20	40	60	80								
	S		14	11.5	10.0	9.0								21
(liquid)	*T*		1 500	1 600	1 700									
	S	20% Co	37.5	40.5	43.5									21
		40% Co	31.5	34.5	36.5									21
		60% Co	28	30	33.5									21
		80% Co	23.6	26	29									21
														also 22
Ni–Cu (liquid)	*T*		1 500	1 600										
	S	20% Cu	41	44.5										21
		40% Cu	37	40										21
		60% Cu	31.5	34.5										21
		80% Cu	23.5	25.5										21
Ni–Fe		*See* Fe–Ni												
Pb (liquid)	*T*	420 500	600	700	800	900	References 45 and 46 report							
	S	— 0.11	0.25	0.45	0.80	1.25	no detected solution for $T < 600$							44
														also 45, 46
Pb–Ca (liquid)			No solution detected in lead with 0.16 or 0.24% Ca at 420 °C											45
Pb–Mg (liquid)	*T*		500	500	500	500	500	500	500	500	500	500	500	
		% Mg	1.0	2.1	3.1	5.5	6.5	7.6	7.8	8.1	8.5	9.0	17.5	
	S		0.18	0.22	0.45	0.87	1.7	1.5	1.8	1.7	2.4	1.9	4.8	45
Pt (solid)	*T*		400	800	1 000	1 100	1 200	1 300						
	S		0.07	0.10	0.19	0.34	0.54	0.80						47
Si (solid)	*T*		1 200											
	S		0.001 6											48
Sn (liquid)	*T*		1 000	1 100	1 200	1 300								
	S		0.04	0.09	0.21	0.36	(results unreliable)							28
Zn (liquid)	*T*		516											
	S		< 0.002											46

Table 12.2 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH ALKALI AND ALKALINE EARTH METAL HYDRIDES

Solvent metal	*Hydride*		*Atom fraction of hydrogen, N_H, and hydride dissociation pressure, P(Pa) at temperature, T °C*								*References*
Ba (solid)	BaH_2	*T*	400	500	600	700					
		N_H	0.18	0.24	0.35	0.50					49
		P	—	—	—	—					
Ca (liquid)	CaH_2	*T*	780	800	830	860					50
		N_H	0.26	0.29	0.31	0.32					also 51, 52
		P	1.87×10^3	3.63×10^3	6.27×10^3	1.08×10^4					
Mg (solid)	MgH_2	*T*	440	470	510	560					53
		N_H	0.020	0.031	0.034	0.093					also 54 and
		P	3.90×10^6	6.55×10^6	1.19×10^7	2.36×10^7					Table 1
Na (liquid)	NaH	*T*	250	300	315	330	350	375	400	425	55, 56
		N_H	9.7×10^{-5}	5.1×10^{-4}	1.2×10^{-3}	2.4×10^{-3}	3.0×10^{-3}	5.8×10^{-3}	1.4×10^{-2}	2.8×10^{-2}	also 58
		P	—	—	—	—	—	—	—	—	

Table 12.2 HYDROGEN SOLUTIONS IN EQUILIBRIUM WITH ALKALI AND ALKALINE EARTH METAL HYDRIDES—*continued*

Solvent metal	*Hydride*	*Atom fraction of hydrogen, N_H, and hydride dissociation pressure, P(Pa) at temperature, T °C*							*References*	
Sr	SrH_2	αSr		γSr—→						
(solid		T 212		263	365	456	497	562	595	57
α+γ)		N_H 0.048		0.062	0.096	0.12	0.14	0.19	0.19	
		P —		—	—	—	—	—	—	
Sr	SrH_2	T 668	740	802	810					57
(solid β)		N_H 0.21	0.26	0.36	0.40					
		P —	—	—	—					

Table 12.3 HYDROGEN SOLUTIONS IN URANIUM EQUILIBRATED WITH GASEOUS HYDROGEN AND WITH URANIUM HYDRIDE
(Mallet and Trzeciak[62], also reference 63)

Solvent phase	*S, mass fraction of hydrogen in uranium equilibrated at T °C with hydrogen gas at atmospheric pressure* *Sp, mass fraction of hydrogen in uranium equilibrated at T °C with uranium hydride, UH_3* *P, UH_3 dissociation pressure* (pascals) *at T °C*								
U	T	100	200	300	400	432	500	600	662
(solid α)	S	—	—	—	—	1.6×10^{-6}	1.8×10^{-6}	2.0×10^{-6}	2.2×10^{-6}
	P	0.2	60	3×10^{3}	5×10^{4}	1.0×10^{5}	3.7×10^{5}	1.81×10^{6}	4.02×10^{6}
	Sp	6×10^{-10}	2×10^{-8}	2×10^{-7}	1.1×10^{-6}	1.6×10^{-6}	3.5×10^{-6}	8.6×10^{-6}	1.35×10^{-5}
	T	662	700	725	750	769			
U	S	7.8×10^{-6}	8.5×10^{-6}	9.0×10^{-6}	—	9.7×10^{-6}			
(solid β)	P	4.02×10^{6}	6.25×10^{6}	8.24×10^{6}	1.05×10^{7}	1.31×10^{7}			
	Sp	4.9×10^{-5}	6.8×10^{-5}	8.1×10^{-5}	9.7×10^{-5}	1.11×10^{-4}			
	T	769	800	900	1 000	1 100	1 129		
U	S	1.47×10^{-5}	1.50×10^{-5}	1.56×10^{-5}	1.62×10^{-5}	1.67×10^{-5}	1.69×10^{-5}		
(solid γ)	P	1.31×10^{7}	2.16×10^{7}	4.07×10^{7}	8.04×10^{7}	1.49×10^{8}	1.77×10^{8}		
	Sp	1.68×10^{-4}	1.95×10^{-4}	3.12×10^{-4}	4.57×10^{-4}	6.43×10^{-4}	7.02×10^{-4}		
	T	1 129	1 200	1 300	1 400				
U	S	2.81×10^{-5}	2.93×10^{-5}	3.11×10^{-5}	3.27×10^{-5}				
(liquid)	P	1.77×10^{8}	2.48×10^{8}	3.94×10^{8}	5.96×10^{8}				
	Sp	1.17×10^{-3}	1.45×10^{-3}	1.94×10^{-3}	2.52×10^{-3}				

Table 12.4 HYDROGEN SOLUTIONS IN HAFNIUM EQUILIBRATED WITH GASEOUS HYDROGEN AT ATMOSPHERIC PRESSURE
(Espagno, Azou and Bastien[70,71], also reference 69)

Temperature °C	100	300	500	700	900	950	1 000	1 050	1 100
Atom ratio H/Hf	1.80	1.78	1.60	1.38	0.88	0.40	0.09	0.06	0.05

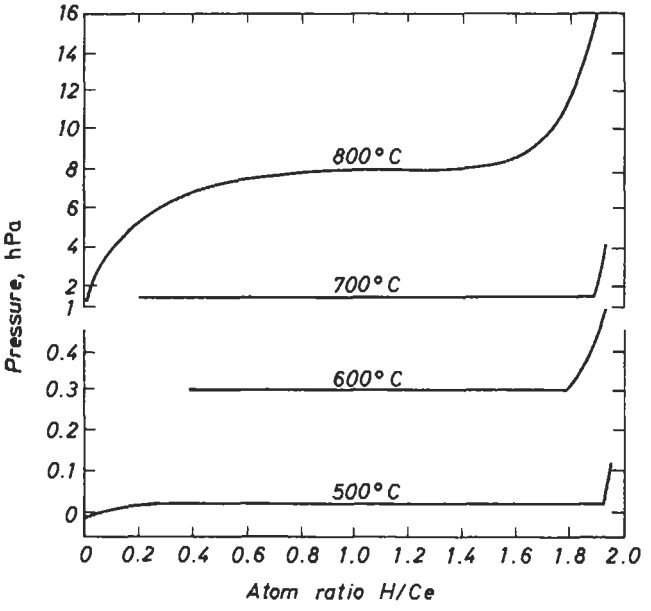


Figure 12.1 *The cerium–hydrogen system (Mulford and Holley.*[64] *See also Sieverts et al.*[65–67] *Ivanov and Stomakhin*[68] *and Edwards and Velekis*[69])

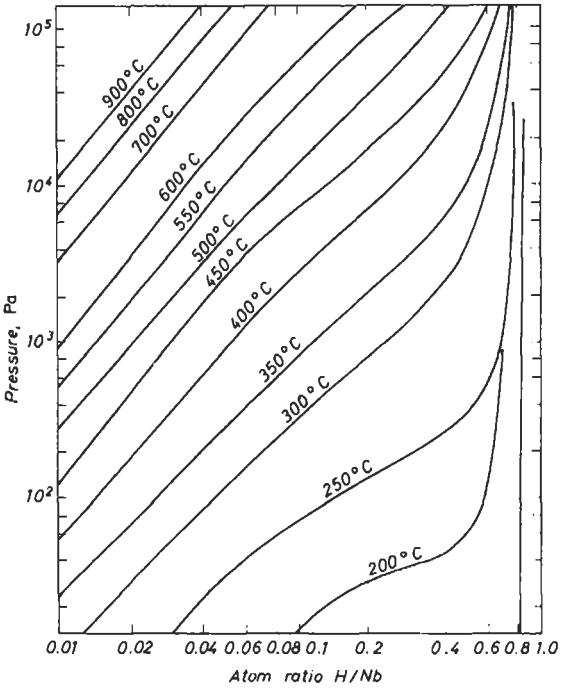


Figure 12.2 *The niobium–hydrogen system (Albrecht, Goode and Mallet.*[73,74] *See also Komjathy*[75] *and Walter and Chandler*[72])

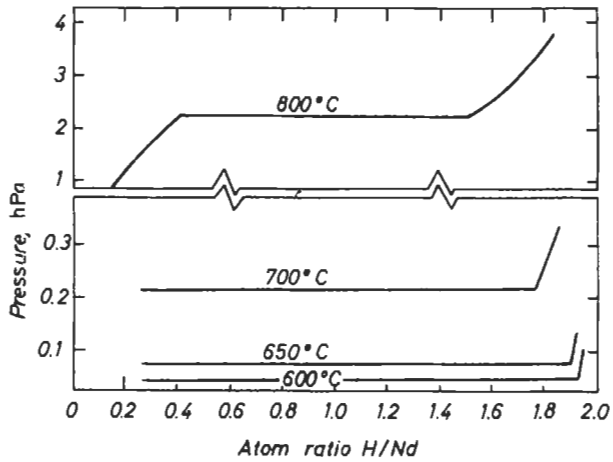


Figure 12.3 *The neodymium–hydrogen system (Mulford and Holley.*[64] *See also Sieverts and Roell*[76]*)*

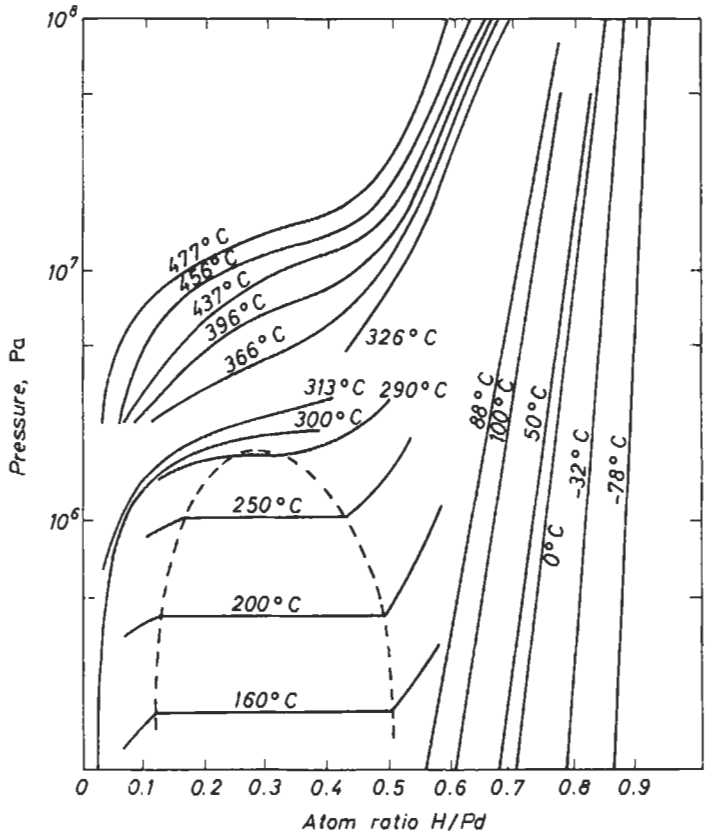


Figure 12.4 *The palladium–hydrogen system (Levine and Weal,*[77] *Gillespie et al.*[78,79] *and Perminov.*[80] *See also Everett and Nordon,*[81] *Flanagan,*[82] *Nakhutin and Sutyagina,*[83] *Mitacek and Aston,*[84] *Carson et al.,*[85] *Karpova and Tverdovsky,*[86] *Vert et al.*[87] *and Maeland and Flanagan*[88]*)*

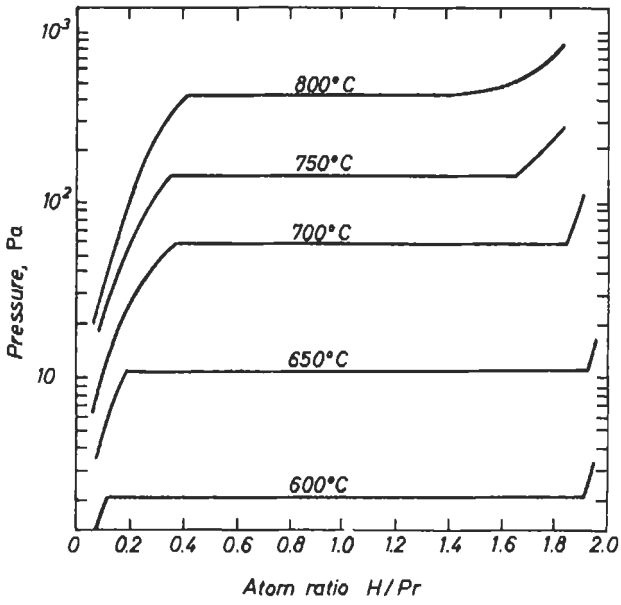


Figure 12.5 *The praseodymium–hydrogen system (Mulford and Holley.*[64] *See also Sieverts and Roell*[76])

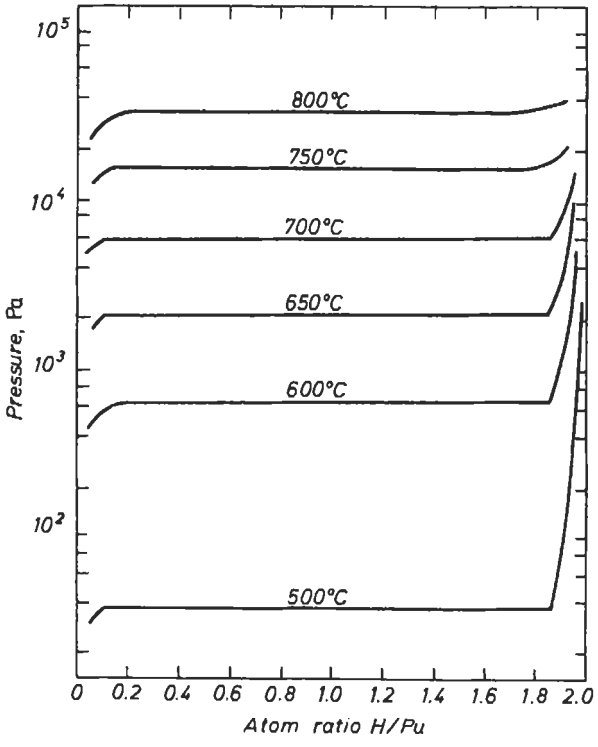


Figure 12.6 *The plutonium–hydrogen system (Mulford and Sturdy*[89])

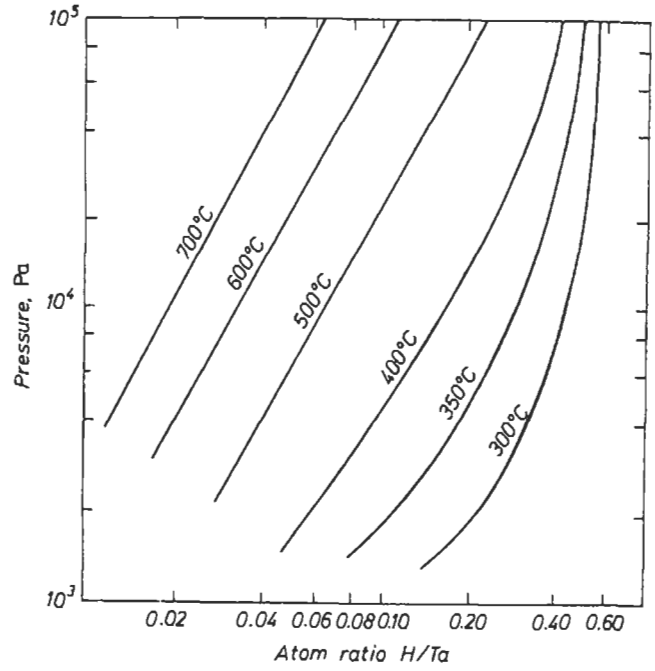


Figure 12.7 *The tantalum–hydrogen system (Mallet and Koehl.*[92] *See also Kofstad et al.*[93] *and Pedersen et al.*[94]*)*

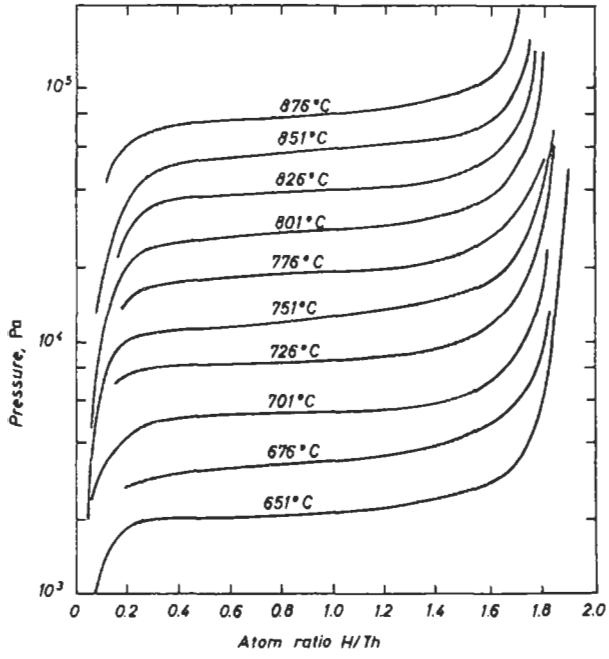


Figure 12.8 *The thorium–hydrogen system (Mallet and Campbell.*[95] *See also Peterson and Westlake*[96]*)*

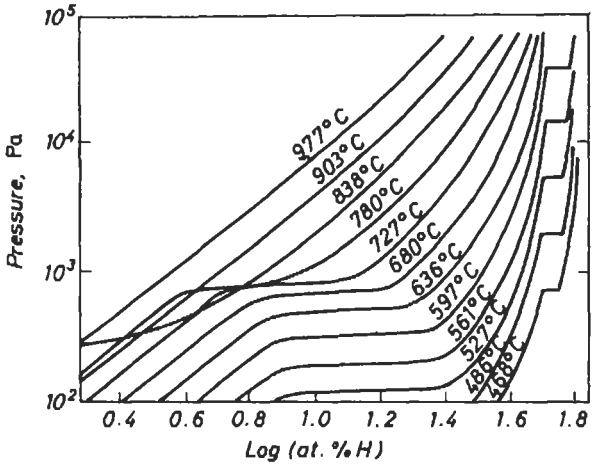


Figure 12.9 *The titanium–hydrogen systems (McQuillan.[97] See also Lenning et al.,[98] McQuillan,[99] Samsonov and Antonova[100] and Krylov[101])*

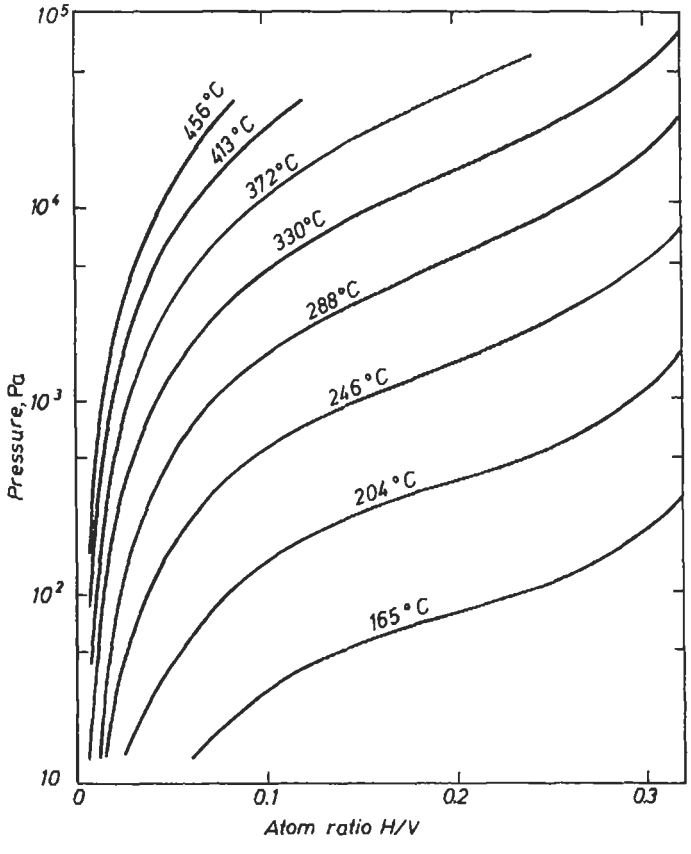


Figure 12.10 *The vanadium–hydrogen system (Kofstad and Wallace.[102] See also Brauer and Schnell[103] and Maeland[104])*

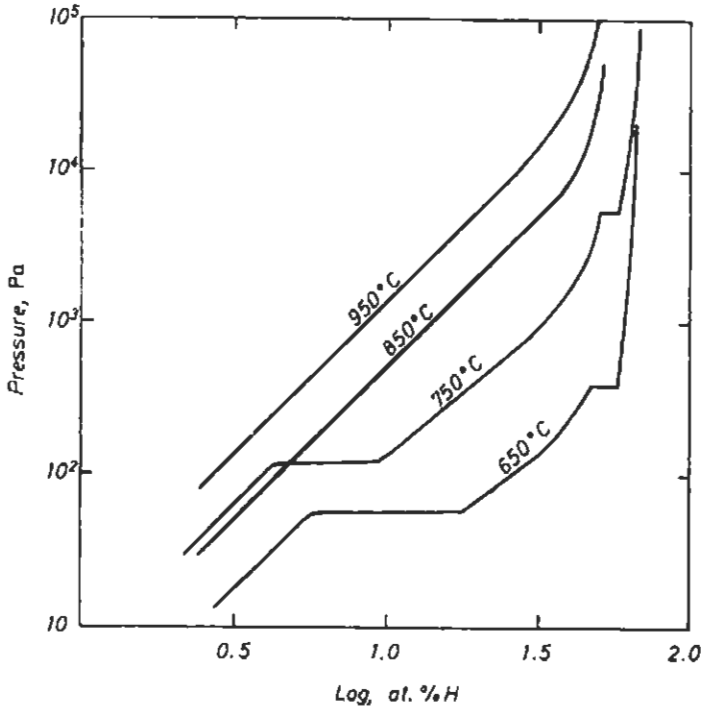


Figure 12.11 *The zirconium–hydrogen system (Private communication from McQuillan based on reference 105. See also Motz,[106] Schwartz and Mallet,[107] Gulbransen and Andrew,[108] Edwards et al.,[109] Mallet and Albrecht,[110] Espagno et al.,[111] Libowitz,[112] La Grange et al.,[113] Slattery,[114] Singh and Gordon Parr,[115] and Kutz and Berger[116])*

12.1.4 Solutions of nitrogen

Table 12.5 gives values of dissolved nitrogen concentration in equilibrium with nitrogen at one atmosphere pressure for the metals iron, cobalt, chromium, molybdenum, manganese, nickel, silicon and some of their alloys. The solutions are dilute and the solution process is endothermic, the solubility increasing with temperature.

Table 12.6 gives values for nitrogen concentrations in iron and chromium in equilibrium with nitrides, measured by methods including internal friction and calorimetry.

In the solid metals, the solute atoms are assumed to occupy interstitial sites, only a small proportion of the available sites being filled. If iron is cold-worked, the nitrogen solubility is enhanced by additional solute sites at lattice defects thereby introduced into the metal (*see* references 117 and 118).

Some transition metals dissolve nitrogen exothermically to form concentrated interstitial solid solutions of metallic character analogous to the corresponding hydrogen solutions. Figures 12.12 and 12.13 present information for the systems niobium–nitrogen and tantalum–nitrogen.

Table 12.5 NITROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS NITROGEN AT ATMOSPHERIC PRESSURE

Solvent metal	*Mass % of nitrogen at temperature, T °C*							*References*
Fe	*T*	700	800	900				
(solid α)	*Mass %*	1.5×10^{-3}	2.3×10^{-3}	3.3×10^{-3}				120 also 119
(solid γ)	*T*	900	1 000	1 100	1 200	1 300	1 400	
	Mass %	0.028	0.025	0.024	0.023	0.022	0.021	120, 121, 122, 145

Table 12.5 NITROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS NITROGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal		*Mass % of nitrogen at temperature, T°C*							*References*
Fe									
(solid δ)	*T*	1 400	1 450	1 500	1 535				
	Mass %	0.010 1	0.011 1	0.012 1	0.012 9				121
(liquid)	*T*	1 600							
	Mass %	0.044	(average of 21 independent determinations)						22, 121, 124–147
Fe–Al	*T*	1 600	1 600						
(liquid)	% Al	0.25	0.5						140
	Mass %	0.044	0.044						
Fe–C	*T*	1 600	1 600	1 600	1 600	1 600			
(liquid)	% C	1	2	3	4	5			125, 128, 131, 132,
	Mass %	0.030	0.022	0.015	0.011	0.004	(averages of independent determinations)		139, 140, 144
Fe–Cr	*T*		1 000	1 100	1 200	1 300	1 400		
(solid γ)	*Mass* %	4.76% Cr	0.102	0.079	0.063	0.051	0.034*		146
		8.67% Cr	0.286	0.193	0.138	0.102	—		
		14.10% Cr	0.96	0.48	0.26	—	—		
			* δ phase						
(liquid)	*T*	1 600	1 600	1 600	1 600	1 600	1 600	1 600	
	% Cr	5	10	15	20	40	60	70	127, 128, 133, 136,
	Mass %	0.07	0.12	0.18	0.29	1.00	2.3	3.5	140 also 143
	T	1 700	1 700	1 700	1 700	1 700	1 700	1 700	
	% Cr	10	20	40	50	70	80	90	
	Mass %	0.10	0.22	0.75	1.16	2.6	3.5	4.5	133
Fe–Co	*T*	1 600	1 600	1 600	1 600	1 600	1 600		
(liquid)	% Co	5	10	20	40	60	80		22, 137, 140, 144
	Mass %	0.040	0.035	0.028	0.023	0.013	0.010		
Fe–Cu	*T*	1 600	1 600	1 600	1 600	1 600			
(liquid)	% Cu	2	4	6	8	10			
	Mass %	0.044	0.042	0.042	0.040	0.039			137, 140, 144
Fe–Mn'	*T*		1 050	1 200	1 300				
(solid γ)	*Mass* %	0.43% Mn	0.025	—	—				
		0.53% Mn	0.024	—	—				119
		1.46% Mn	0.025	—	0.020				
		12.98% Mn	0.066	0.046	—				
	T	1 550	1 550	1 550	1 550	1 550	1 550		
(liquid)	% Mn	5	10	20	40	60	80		
	Mass %	0.044	0.052	0.087	0.22	0.43	0.80		141, 142
	T	1 600	1 600	1 600	1 600	1 600			
	% Mn	1	2	5	10	20			
	Mass %	0.046	0.048	0.060	0.074	0.098			133, 140 also 143
Fe–Mo	*T*	1 600	1 600	1 600	1 600	1 600			
(liquid)	% Mo	2	4	6	8	10			135, 137, 140, 144
	Mass %	0.045	0.047	0.051	0.054	0.057			also 143
Fe–Nb	*T*	1 600	1 600	1 600	1 600				
(liquid)	% Nb	2	4	6	8				
	Mass %	0.060	0.085	0.11	0.16				140, also 143
Fe–Ni	*T*		918	999	1 217				
(solid)	*Mass* %	1.01% Ni	0.028 3	0.025 3	0.021 5				
		3.98% Ni	0.025 2	0.021 9	0.018 7				
		8.11% Ni	0.020 5	0.018 6	0.015 6				145 also 143
		15.46% Ni	0.013 2	0.012 5	0.011 1				
		26.8% Ni	0.006 1	0.006 2	0.006 1				
		40.7% Ni	0.001 9	0.002 3	0.002 7				

Table 12.5 NITROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS NITROGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal	*Mass % of nitrogen at temperature, T °C*									*References*
Fe–Ni (liquid)	*T*	1 600	1 600	1 600	1 600	1 600	1 600			137
	% Ni	1	2	5	10	25	50			131, 132, 133, 135,
	Mass %	0.044	0.043	0.039	0.033	0.017	0.006 7			136, 140, 144 also 143
Fe–O (liquid)	Effect of up to 0.2% O is slight									140
Fe–S (liquid)	Effect of up to 0.3% S is slight									137, 140, 144
Fe–Si (solid α)	*T*		700	800	900	1 000	1 100			
	Mass %	2.83% Si	0.001 3	0.001 6	0.001 9	0.002 1	0.002 4			120
(solid γ)	*T*		1 000	1 050	1 100	1 200	1 300	1 350		
	Mass %	0.20% Si	—	0.024	—	0.022	—	0.020		
		0.58% Si	—	0.022	—	0.020	—	0.018		122, 147
		0.90% Si	0.024	—	0.022	0.021	0.020	—		
		1.26% Si	0.023	—	0.022	0.021	0.019	—		
(liquid)	*T*	1 600	1 600	1 600	1 600	1 600				
	% Si	2	4	6	8	10				126, 140, 144
	Mass %	0.035	0.026	0.020	0.013	0.010				also 143
Fe–Sn (liquid)	*T*	1 600	1 600	1 600	1 600	1 600				
	% Sn	2	4	6	8	10				
	Mass %	0.044	0.042	0.041	0.041	0.040				137, 140
Fe–Ta (liquid)	*T*	1 600	1 600	1 600	1 600	1 600				
	% Ta	2	4	6	8	10				
	Mass %	0.052	0.060	0.072	0.084	0.098				140
Fe–V (liquid)	*T*		1 600	1 700	1 800	1 900				
	Mass %	1% V	0.059	0.059	0.059	0.059				
		2% V	0.074	0.071	0.070	0.067				
		3% V	0.088	0.084	0.081	0.079				135, 140
		5% V	—	0.129	0.120	0.110				
		10% V	—	0.315	0.280	0.237				
Fe–W (liquid)	*T*	1 600	1 600	1 600	1 600	1 600	1 600	1 600		
	% W	2	4	6	8	10	12	14		
	Mass %	0.044	0.044	0.045	0.045	0.046	0.046	0.046		140
Fe–Cr–Ni (liquid)	*T*	1 600	1 600	1 600	1 600	1 600	1 600	1 600		
	% Cr	8.9	13.4	4.0	23.0	33.3	24.7	50.0		
	% Ni	6.5	13.4	29.5	6.0	33.1	50.6	25.0		136
	Mass %	0.083	0.255	0.041	0.316	0.476	0.762	1.35		
	For additional data *see* reference 136									
Fe–Mo–V	*T*	1 700	1 700	1 700	1 700	1 700	1 700	1 700	1 700	1 700
	% Mo	1	3	5	1	3	5	1	3	5
	% V	1	1	1	2	2	2	3	3	3
	Mass %	0.054	0.058	0.063	0.069	0.071	0.077	0.089	0.093	0.099 135
	For additional data *see* reference 135									
Co (solid)	Not detectable for *T* 1 200									149, 150
(liquid)	*T*	1 600								
	Mass %	0.004 7								151
Co alloys (liquid)	*T*	1 600	1 600	1 600	1 600	1 600				
	alloying element	0.8% Al	3.0% Cr	6.0% Cu	1.0% Fe	6.0% Mo				
	Mass %	0.004 4	0.006 4	0.005 3	0.004 6	0.005 3				151
	T	1 600	1 600	1 600	1 600	1 600	1 600			
	alloying element	5.5% Nb	3.5% Ni	1.8% Si	6.0% Ta	1.0% V	6.0% W			
	Mass %	0.009 8	0.003 9	0.002 8	0.007 2	0.005 9	0.005 3			151

Table 12.5 NITROGEN SOLUTIONS IN EQUILIBRIUM WITH GASEOUS NITROGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal		*Mass % of nitrogen at temperature, T °C*							*References*
Co–Fe	*See* Fe–Co								
Cr	*T*	1 600	1 650	1 700	1 725	1 750			
(liquid)	*Mass* %	4.08	3.90	3.84	3.76	3.54			154 also 136, 153
Cr–Ni	*See* Ni–Cr								
Cr–Si	*T*		1 600	1 650	1 700	1 750			
(liquid)	*Mass* %	1.5% Si	3.83	3.68	3.54	3.08			
		7.5% Si	1.98	1.89	1.72	1.68			154
		10.0% Si	0.84	0.74	0.69	0.62			also 153
		20.0% Si	0.33	0.30	0.28	0.26			
Mo	*T*	950	1 000	1 050	1 100	1 150			
(solid)	*Mass* %	0.85	0.56	0.41	0.33	0.26			155
Mn	*T*	1 245	1 300	1 400	1 500	1 600	1 700		
(liquid)	*Mass* %	3.4	2.8	1.9	1.6	1.1	1.0		146, 156
Mn–Fe	*See* Fe–Mn								
Ni	*T*	1 600							22, 136, 137, 144
(liquid)	*Mass* %	< 0.002 5							
Ni–Cr	*T*	1 600	1 600	1 600	1 600	1 600	1 600	1 600	
(liquid)	% Cr	10	20	30	40	50	60	70	136
	Mass %	0.016	0.068	0.17	0.44	1.0	1.7	2.6	
Ni–Fe	*See* Fe–Ni								
Si	*T*	1 420							
(liquid)	*Mass* %	~0.01							129
U	Some phase relationships discussed in references 171 and 172								

Table 12.6 NITROGEN SOLUTIONS IN IRON AND CHROMIUM IN EQUILIBRIUM WITH NITRIDES

Solvent	*Phase in equilibrium*	*Method of determination*	*Mass % of nitrogen at temperature, T °C*	*References*
Pure α Fe	Fe_4N	Calorimetry	*T* 200 240 300 330 400 450 575	
			Mass % 0.008 0.014 0.018 0.026 0.043 0.059 0.097	160
		Invariant pressure	*T* 450 500 550 590	
			Mass % 0.033 — 0.070 0.10	161
			— 0.06 — —	117
		Internal friction	*T* 250 300 350 400 450 500 575 585*	
			Mass % 0.005 0.010 0.015 0.025 0.035 0.050 0.075 —	162
			— 0.008 4 — 0.025 — 0.055 — 0.095	163
			*eutectoid temperature	
			See also criticism in reference 164 and reply in reference 165	
	Fe_8N	Internal friction	*T* 20 100 150 200 250 300 400	
			Mass % — — 0.003 5 0.010 0.020 0.040 —	162
			1.4×10^{-5} 5.2×10^{-4} — 0.008 8 — 0.055 0.20	163
	N_2 at 1 atm (for comparison)	Internal friction	*T* 500 585 700 800 900	
			Mass % 9.0×10^{-4} 0.001 4 0.002 4 0.003 3 0.004 5	163
			See also Table 12.8	
Fe–2.8% Si	Unidentified nitride	Internal friction	*T* 300 400 500 600 700 800 900 1 000	
			Mass % 0.001 0 0.001 5 0.002 4 0.004 0 0.006 1 0.010 0.014 0.019	166
Cr (solid)	Cr_2N		*T* 1 100 1 200 1 300 1 400	
			Mass % 0.04 0.09 0.14 0.26	152
			P_{Cr_2N} Pa 2×10^2 9×10^2 2.5×10^3 5.8×10^3	

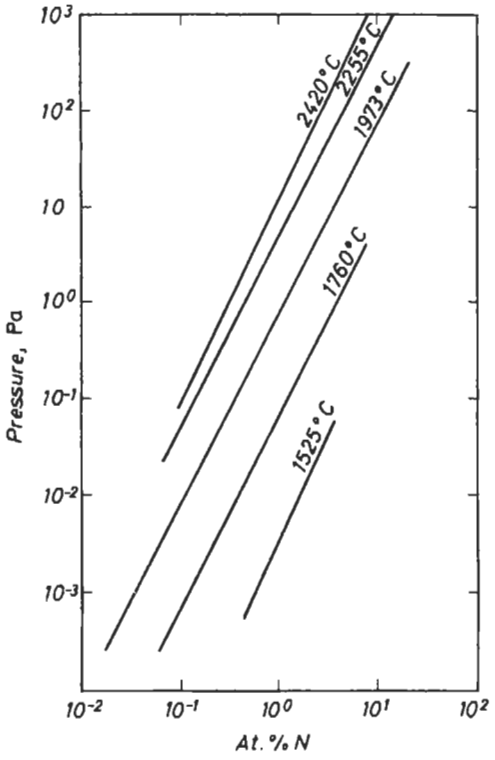


Figure 12.12 *The niobium-nitrogen system (Cost and Wert*[168] *See also Pemsler*[167]*)*

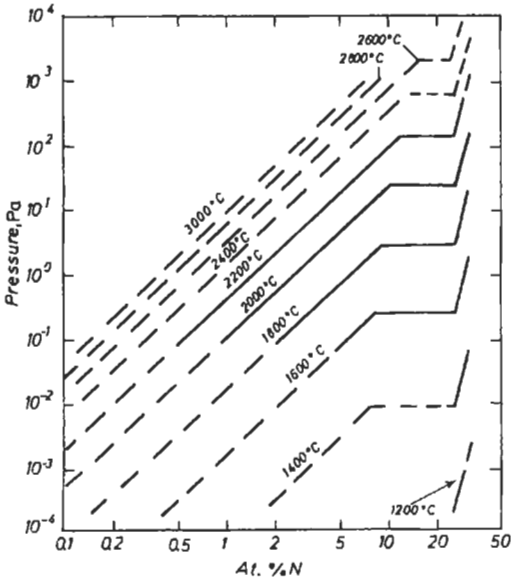


Figure 12.13 *The tantalum–nitrogen system (Gebhardt et al.*[169] *See also Gebhardt et al.*[170] *and Pemsler*[167]*)*

12.1.5 Solutions of oxygen

The free energies of formation of the lowest oxides of most metals are comparatively high, so that an oxide film is formed when these metals are exposed to oxygen, except for very low pressures or very high temperatures. The solubility data usually required is therefore the concentration of dissolved oxygen in equilibrium with the oxide phase. A few other metals (Os, Pt, Rh, Au, Hg, Pd, Ru and Ir) form less stable oxides so that no film is present when the metals are exposed to oxygen at atmospheric pressure at elevated temperature. Of these, only silver and palladium dissolve appreciable quantities of oxygen. Table 12.7 gives values for the dissolved concentrations of oxygen in equilibrium with the lowest oxide of the metal or with gaseous oxygen at atmospheric pressure as appropriate. These concentrations are often small and difficult to measure. The usual method of establishing equilibrium by allowing oxygen to diffuse inwards from a surface oxide phase or from the gas phase is liable to lead to erroneous results unless the metal is free from traces of impurities which form oxides more stable than its own oxide.

Some transition metals can dissolve large quantities of oxygen before a separate oxide phase appears. Figures 12.14 and 12.15 give isotherms for the systems niobium–oxygen and tantalum–oxygen.

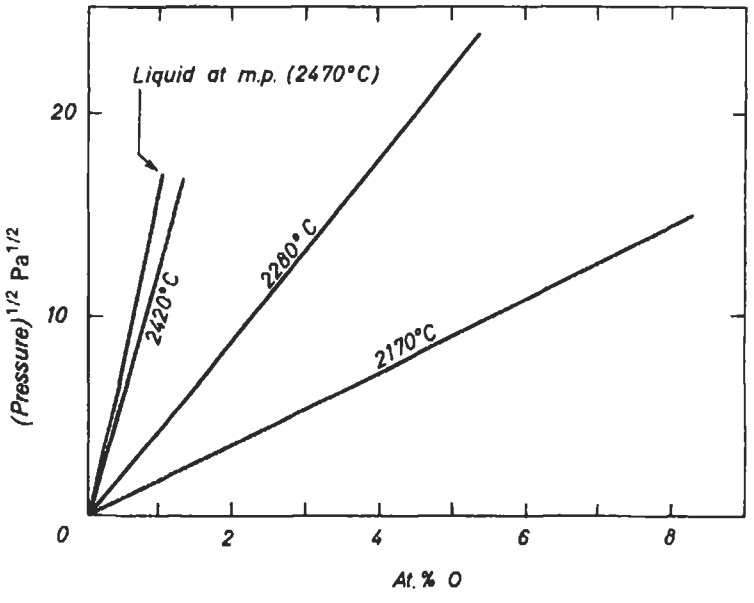


Figure 12.14 *The niobium–oxygen system (Pemsler.[167] See also Elliot[210] and Fromm[208])*

Table 12.7 OXYGEN SOLUTIONS IN EQUILIBRIUM WITH OXIDES OR WITH GASEOUS OXYGEN AT ATMOSPHERIC PRESSURE

Solvent metal	*Phase in equilibrium*	*Mass % of oxygen at temperature, T °C*							*References*	
Ag	O_2 (gas at	*T*	300	400	500	600	700	800	900	
(solid)	atmospheric pressure)	*Mass %*	3.0×10^{-5}	1.4×10^{-4}	4.4×10^{-4}	1.07×10^{-3}	2.16×10^{-3}	3.81×10^{-3}	6.14×10^{-3}	174 also 173
(liquid)	O_2 (gas at	*T*	973	1 024	1 075	1 125				
	atmospheric pressure)	*Mass %*	0.305	0.295	0.277	0.264				173
Co	CoO	*T*	600	700	810	875				
(solid α)	(solid)	*Mass %*	0.6×10^{-2}	0.9×10^{-2}	1.6×10^{-2}	2.05×10^{-2}				175
(solid β)	CoO	*T*	875	945	1 000	1 200				
	(solid)	*Mass %*	0.58×10^{-2}	0.7×10^{-2}	0.8×10^{-2}	1.3×10^{-2}				175
(liquid)	CoO	*T*	1 550	1 600	1 650					
	(solid)	*Mass %*	0.13	0.16	0.23					178
Cr	Cr_2O_3	*T*	1 350							
(solid)	(solid)	*Mass %*	approximately 0.03%							179
Cu	Cu_2O	*T*	600	700	800	900	950	1 000	1 050	
(solid)	(solid)	*Mass %*	1.6×10^{-3}	1.7×10^{-3}	2.1×10^{-3}	2.7×10^{-3}	3.4×10^{-3}	4.6×10^{-3}	7.7×10^{-3}	181 also 180, 176, 177
Fe	FeO	*T*	< 1 500							
(solid)	(solid)	*Mass %*	< 0.009							182, 189
(liquid)	FeO	*T*	1 550	1 600	1 650	1 700				
	(liquid)	*Mass %*	0.18	0.23	0.28	0.34				183, 184, 185, 186, 187, 188, 267, 189, 268
Hf		*See* references 190 and 191								
K	K_2O	*T*	100	150	200	250	300			
(liquid)	(solid)	*Mass %*	0.10	0.17	0.27	0.41	0.60			192
Li	Li_2O	*T*	250	400						
(liquid)	(solid)	*Mass %*	0.0109	0.066						193
Mo		*See* reference 194 for condensed-phase relationships								194
Na	Na_2O	*T*	100	200	300	400	500	550		
(liquid)	(solid)	*Mass %*	0.002	0.005	0.010	0.018	0.047	0.08		192

Table 12.7 OXYGEN SOLUTIONS IN EQUILIBRIUM WITH OXIDES OR WITH GASEOUS OXYGEN AT ATMOSPHERIC PRESSURE—*continued*

Solvent metal	*Phase in equilibrium*	*Mass % of oxygen at temperature, T °C*						*References*
Nb		*See* Figure 12.14 and references 167, 205, 206, 207 and 210						
Ni	NiO	*T*	600	800	1 000	1 200		
(solid)	(solid)	*Mass* %	0.020	0.019	0.014	0.012		195
(liquid)	NiO	*T*	1 450	1 500	1 550	1 600	1 650	
	(liquid)	*Mass* %	0.28	0.46	0.72	1.10	1.66	199
See also references 178, 197 and 198 for activities of O in Ni–Fe and Ni–Co alloys								also 196, 197, 198
Pb	PbO	*T*	350	450	550			
(liquid)	(solid)	*Mass* %	5.4×10^{-4}	8.6×10^{-4}	13.2×10^{-4}			200
Pd	O_2 (gas at	*T*	1 200					
(solid)	atmospheric pressure)	*Mass* %	<0.05					201
Pu		*See* reference 209 for plutonium–oxygen phase diagram						
Rh	O_2 (gas at	Slight solubility						
(solid)	atmosphere pressure)							201
Si	SiO_2	*T*	1 000	1 100	1 200	1 300	1 412	
(solid)	(solid)	*Mass* %	2.8×10^{-4}	5.3×10^{-4}	9.1×10^{-4}	1.5×10^{-3}	2.2×10^{-3}	202, 203
Sn	SnO_2	*T*	536	600	700	751		
(liquid)	(solid)	*Mass* %	0.000 18	0.000 55	0.002 8	0.004 9		204
Ta		*See* Figure 12.15 and references 208 and 210–220						
Ti		*See* references 221–229						
U		*See* references 230–232						
V		*See* references 233–236						
Y		*See* reference 237						
Zr		*See* references 238–242						

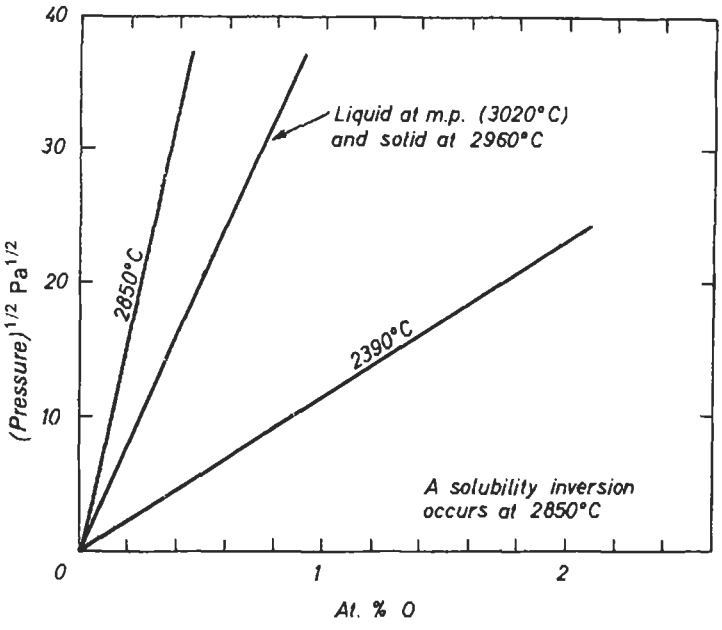


Figure 12.15 *The tantalum–oxygen system (Pemsler.*[167] *See also Gebhardt et al.,*[205,212–218] *Powers and Doyle,*[219] *Marcotte and Larsen,*[206] *Meussner and Carpenter*[207] *and Fromm*[208])

12.1.6 Solutions of the noble gases

The solubilities in metals of the noble gases in Group 8 of the Periodic Table are so small that the quantities which dissolve by equilibrating metals with the pure gases are difficult to detect. For example, Kubaschewski's theoretical argument[1] predicts that at 600°C, only 3.5×10^{-10} atomic fraction of xenon will dissolve in liquid bismuth equilibrated with xenon gas at one atmosphere pressure. However, significant quantities of the noble gases can be inserted into metal lattices by very energetic processes such as nuclear fission or bombardment with accelerated ions. Examples of solutions produced in this manner are given in Table 12.8. Fuller information is given in a review by Blackburn.[14]

Table 12.8 SOLUTIONS OF NOBLE GASES

Solvent	*Solutes*	*Method of introducing solute*	*References*
Ag	Ar, Kr, Xe	Electric discharge on metal in gas at low pressure	243, 244, 246, 247, 249
	Ar	Injection of accelerated ions	245
	Kr	Equilibration with gas phase	248
Al	Ar	Injection of accelerated ions	245
	He	Injection of cyclotron-accelerated α-particles	250, 251, 252
Al–Li	He	Radioactive decay of neutron-irradiation products	253, 254
Al–U	Kr	Radioactive decay of neutron-irradiation products	255
Au	Ar	Injection of accelerated ions	245
Be	He	Radioactive decay of neutron-irradiation products	256, 257
	He	Injection of cyclotron-accelerated α-particles	258
Cu	He	Injection of cyclotron-accelerated α-particles	250, 259
Ge	He	Equilibration with gas phase	48, 260
Pb	Ar	Injection of accelerated ions	245
	K	Equilibration with gas phase	248

Table 12.8 SOLUTIONS OF NOBLE GASES—*continued*

Solvent	*Solutes*	*Method of introducing solute*	*References*
Si	He	Equilibration with gas phase	48, 260
Sn	Kr	Equilibration with gas phase	248
Ti	He		261
U	Ar, Kr, Xe	Electric discharge on metal in gas at low pressure	243, 244
	Kr	Injection of accelerated ions	245
	Kr, Xe	Nuclear fission of solvent	262, 263, 264, 265, 266
Zr	Ar, Kr, Xe	Electric discharge on metal in gas at low pressure	243, 244

12.1.7 Theoretical and practical aspects of gas–metal equilibria

The equilibria between metals and gases are of a wide variety and the practical effects of absorbed gases in metals during industrial processes are diverse, usually deleterious and often difficult to assess. As a result, a vast amount of practical and theoretical effort has been applied in studying gas–metal interactions using numerous different approaches, as illustrated by the selection of reviews and papers of general or theoretical interest given in references 1–15.

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13 Diffusion in metals

13.1 Introduction

In an isotropic medium the diffusion coefficient D^i of species i is defined through Fick's first law,

$$J^i = -D^i \text{ grad } c^i \tag{13.1}$$

J^i is the instantaneous net flux of species i, or diffusion current per unit area, and grad c^i is the gradient of the concentration c^i of i. If J and c are measured in terms of the same unit of quantity (e.g. J in g cm^{-2} s^{-1}, c in g cm^{-3}), D has the dimensions (L^2T^{-1}). It has usually been expressed as cm^2 s^{-1}, although the units m^2 s^{-1} are becoming more common. Generally, D depends on the concentration.

That matter is to be conserved at each point leads to Fick's second law,

$$\frac{\partial c^i}{\partial t} = \text{div } (D^i \text{ grad } c^i) \tag{13.2}$$

giving the rate of the change of concentration with time to which diffusion gives rise.

The fluxes J^i are referred, at least for practical purposes, to axes fixed in the volume of the sample; but volume changes which take place as a result of diffusion lead to some ambiguity in the definition of such axes. Means have been proposed[3,6] for avoiding this by using axes scaled to the volume changes, but little use is made of these and it is more usual in accurate work to restrict the range of concentration employed so that volume changes are small or negligible.

When the concentration varies along only one direction, say the x axis, (13.1) and (13.2) become

$$J^i = -D^i \frac{\partial c^i}{\partial x} \tag{13.3}$$

$$\frac{\partial c^i}{\partial t} = \frac{\partial}{\partial x}\left(D^i \frac{\partial c^i}{\partial x}\right) \tag{13.4}$$

If, furthermore, D is independent of composition, and so also of position in the sample, (13.4) becomes

$$\frac{\partial c^i}{dt} = D^i \frac{\partial^2 c^i}{\partial x^2} \tag{13.5}$$

In anisotropic media diffusion rates vary with direction. In general, the diffusion flux is in the same direction as grad c *only* when grad c is along one of a set of orthogonal axes known as the 'principal axes of diffusion'. (These always coincide with axes of crystallographic symmetry so there is no difficulty in identifying them, except in cases of symmetry lower than orthorhombic.) For diffusion along principal axes equations like (13.3) may still be written.

$$\left.\begin{aligned} J^i_x &= -D^i_x(\partial c^i/\partial x) \\ J^i_y &= -D^i_y(\partial c^i/\partial y) \\ J^i_z &= -D^i_z(\partial c^i/\partial z) \end{aligned}\right\}$$

D_x, D_y and D_z are called 'principal coefficients of diffusion'.

In general grad c and J are not in the same direction. However, if l, m, n are the direction cosines of grad c then a diffusion coefficient for this direction may be defined as the ratio of the

component of J along (l, m, n), divided by grad c. This is

$$D_{lmn}=l^2D_x+m^2D_y+n^2D_z \tag{13.6}$$

Thus anisotropic diffusion can be completely described in terms of the three principal diffusion coefficients. In uniaxial crystals (tetragonal, trigonal, hexagonal) symmetry dictates, if the z axis is the unique axis, that $D_x=D_y$. Thus D is the same for all directions perpendicular to the unique axis and is often denoted $D_\perp$. D_z is then denoted as $D_\parallel$. (13.6) may then be written

$$D_\theta=\sin^2\theta\cdot D_\perp+\cos^2\theta\cdot D_\parallel \tag{13.7}$$

where $\cos\theta\equiv n$.

Equations (13.4) and (13.5) still hold for anisotropic diffusion, with D given by (13.6) and (13.7).

Equation (13.1) provides a formal definition of a diffusion coefficient as the ratio of J^i to grad c^i. It also assumes that J^i is determined only by grad c^i. In the very large majority of diffusion measurements that have been made this holds true so that the above simple equations provide an adequate description of the diffusion process taking place. Such measurements are of three main types and these are discussed first and the nature of the diffusion coefficients they entail. They are:

1. Measurements which entail diffusion under a chemical concentration gradient (Chemical Diffusion Measurements—Table 13.4).

 (i) Diffusion of a single interstitial solute into a pure metal.
 (ii) Interdiffusion of two metals which form substitutional solid solutions (or interdiffusion between two alloys of the two metals).

2. Measurements which entail diffusion in essentially chemically homogeneous systems. These are possible through the use of radioactive or stable isotope tracers.

The diffusion of an interstitial solute in a pure metal [1(i)] is described by a single equation like (13.1) and the D has a simple and well-defined physical significance as describing diffusion of solute relative to the solvent lattice.

The same is true for the D for diffusion into a metal or alloy of any radioactive or stable tracer. The methods employed (*see* below) require such extremely small amounts and gradients of tracer that the system remains chemically homogeneous during diffusion. Any diffusion of other constituents is altogether negligible so that D refers simply to the diffusion of the tracer species relative to the solvent lattice.

For the interdiffusion of two metals or alloys [1(ii)] the situation is a little less simple. There would appear to be two diffusion coefficients required, one for each species, but *referred to volume fixed axes* these are equal because grad $c_1=-$grad c_2 and J_1 must be equal and opposite to J_2. Again a single equation like (13.1) suffices to describe the diffusion process and the single D refers to the diffusion rate of either species relative to these axes. It is called the *chemical interdiffusion coefficient* and usually denoted $\tilde{D}$ (Table 13.4).

For many practical purposes $\tilde{D}$ is an adequate measure of the diffusion behaviour of a binary substitutional system. But of more fundamental physical interest are the rates of diffusion of the two species relative to local lattice planes. It is well established that generally these rates are not equal in magnitude. There is therefore a net total flux of atoms across any lattice plane, and if the density of lattice sites is to be conserved each plane in the diffusion zone must shift to compensate for this imbalance of the fluxes across it. At the same time lattice sites are created on one side of the sample and eliminated at the other, processes which are achieved by the creation and annihilation of vacancies. This shift of lattice planes, known as the Kirkendall effect, is observed experimentally as a movement of inert markers, usually fine insoluble wires, incorporated into the sample before diffusion. It is clear, then, that diffusion occurs on a lattice which locally is moving relative to the axes with respect to which $\tilde{D}$ was calculated. To provide a more complete description of binary substitutional diffusion it is therefore necessary to introduce diffusion coefficients D_A and D_B to describe diffusion of the two species relative to lattice planes. It is easy to show that these are related to $\tilde{D}$ by the equation

$$\tilde{D}=N_AD_B+N_BD_A \tag{13.8}$$

where N_A and N_B are the fractional concentrations of A and B. D_A and D_B, which are of more direct physical interest than $\tilde{D}$, are known as the *intrinsic* or *partial chemical diffusion coefficients*.

The velocity v of a marker is given by

$$v=(D_A-D_B)\partial N_A/\partial x, \tag{13.9}$$

where $\partial N_A/\partial x$ is the concentration gradient at the marker; so in principle D_A and D_B can be calculated separately when $\tilde{D}$ and v have been measured. In practice this is done usually only for

markers placed at the original interface between the two interdiffusing metals or alloys: in this case a measurement of the *displacement* x_m of the marker after time t allows v to be obtained simply, for $v = x_m/2t$.

Equations (13.8) and (13.9) assume no net volume change and a compensation of the flux difference which is complete and which occurs by bulk motion along only the diffusion direction. These conditions are rarely met fully in practice, as is seen from the occurrence often of lateral changes in dimensions and of a porosity in the *side* of the diffusion zone suffering a net loss of atoms. This porosity, attributed to vacancies precipitating instead of being eliminated at sinks, suggests abnormal vacancy concentrations may be present in the diffusion zone. Because it is difficult to take into account the effect these abnormal conditions in the diffusion zone may have on the calculated values of $\tilde{D}$ and v, and hence on D_A and D_B, chemical interdiffusion experiments may provide results of limited accuracy and, for theoretical purposes, of limited significance: their effect is of course smaller the smaller the concentration gradients employed.

By contrast, radioactive tracer methods altogether avoid these difficulties and uncertainties associated with diffusion in a chemical gradient, and so are preferred in any investigation with a theoretical objective. They have the further advantage that the diffusion coefficients of the several species of an alloy can be determined separately and directly, rather than through any composite coefficient like $\tilde{D}$. These are referred to as *tracer diffusion coefficients* (Table 13.3) and will be denoted D_A^*, D_B^* etc. to distinguish them from the partial chemical diffusion coefficients D_A and D_B determined by chemical diffusion methods.†

Results on the diffusion coefficient D_A^* in very dilute alloys AB containing small concentrations C_B of B are frequently represented in terms of the solvent enhancement factors b_1, b_2, etc., in the equation

$$D_A^*(C_B) = D_A^*(C_B=0)\,(1 + b_1 C_B + b_2 C_B^2 + \ldots) \tag{13.9a}$$

$D_A^*(C_B=0)$ is of course just the self-diffusion coefficient of pure A.

A similar relation describes the diffusion of the solute B in A

$$D_B^*(C_B) = D_B^*(C_B=0)\,(1 + B_1 C_B + B_2 C_B^2 + \ldots) \tag{13.9b}$$

B_1, B_2 are the solute enhancement factors and $D_B^*(C_B=0)$ is the tracer impurity diffusion coefficient of B in A.

Except at vanishingly small concentrations of A, D_A and D_A^* differ fundamentally because the presence of the chemical concentration gradient under which D_A is measured imposes on the otherwise random motion of the atoms a bias, which makes atoms jump preferentially in one direction along the concentration gradient. Simple thermodynamic considerations lead to the relation

$$D_A = D_A^*\left(1 + \frac{\partial \ln \gamma_A}{\partial \ln N_A}\right) \tag{13.10}$$

between a partial chemical D_A and the corresponding tracer D_A^* measured at the same concentration. γ_A is the activity coefficient of A. In a binary system the bracket term is the same for both species (Gibbs–Duhem relation). Thus

$$\frac{D_A}{D_A^*} = \frac{D_B}{D_B^*} \tag{13.11}$$

(13.10) and (13.11) are approximate forms of more elaborate theoretical expressions, but are reasonably well obeyed experimentally. See, for example, references 4 and 7.

When D_A^* is measured at the extremely small concentrations of A that tracer methods permit (by diffusion of tracer into pure metal B) it is called the *tracer impurity diffusion coefficient* of A in B (Table 13.2). Such coefficients are of especial theoretical interest because of the particularly simple type of diffusion they describe (*see* footnote).

Finally, tracer methods are used as the commonest means of measuring *self-diffusion coefficients* in pure metals (Table 13.1, 13.5 and 13.6). By self-diffusion is meant of course the diffusion of a species in the pure lattice of its own kind.

For chemical diffusion in systems of more than two components, equation (13.1) and those following are inadequate. Experimentally it is found that when three or more components are

† D_A^* and D_B^* are sometimes referred to as the *self-diffusion coefficients of the alloy*. This is a perfectly acceptable alternative terminology. But there is a tendency nowadays to employ the term 'self' to the extent of describing tracer impurity diffusion coefficients (*vi*) as impurity self-diffusion coefficients. This latter term is ambiguous and misleading and its use is to be discouraged.

present a concentration gradient of one species can lead to a diffusion flow of another, even if this is distributed homogeneously to start with. To cater for such cases Fick's first law is generalized by writing

$$J_i = \sum_{j=1}^{N} D_{ij} \frac{\partial c_j}{\partial x} \qquad (j = 1, 2 \ldots N) \tag{13.12}$$

But if there are n interstitial and $N-n$ substitutional components, and if the J_i are referred to volume-fixed axes then the relations

$$\sum_{j=n+1}^{N} J_i = 0 \quad \text{and} \quad \sum_{j=n+1}^{N} \partial c_j / \partial x = 0$$

allow (13.12) to be rewritten

$$J_i = \sum_{j=1}^{N-1} D_{ij} \frac{\partial c_j}{\partial x} \qquad (j = 1, 2 \ldots N-1) \tag{13.13}$$

so that $(N-1)^2$ coefficients suffice to describe the diffusion behaviour. The analogue of Fick's second law is

$$\frac{\partial c_i}{\partial t} = \sum_{j=1}^{N-1} \frac{\partial}{\partial x}\left(D_{ij} \frac{\partial c_j}{\partial x} \right) \tag{13.14}$$

These equations have been applied to a few ternary systems.[7]

It is possible to show from the principles of irreversible thermodynamics that not all the D_{ij} are independent and that a total of only $N(N-1)/2$ coefficients are in fact sufficient to describe diffusion in an N-component system. No measurements in metals have employed this reduced scheme of coefficients, for to do so requires a knowledge of the thermodynamic properties of the system that is rarely available.

13.2 Methods of measuring D

13.2.1 Steady-state methods

These are based directly on Fick's first law. The usual procedure is to maintain concentrations of diffusant on the opposite sides of a sample, which is usually a thin sheet or a thin-walled tube, and to measure the resulting steady rate of flow J. This is generally practicable only when the diffusing element is a gas or can be supplied to and removed from the sample through a vapour phase. If the surface concentrations c_1 and c_2 in equilibrium with the ambient atmospheres are known, an average D over the concentration range is, for a sheet of thickness t for example, simply $\bar{D} = Jt/(c_1 - c_2)$ (Method Ib). Alternatively, if the steady concentration distribution across the sample is determined, $D(c)$ may be calculated from $D = J(\partial c/\partial x)$ (Method Ia).

D may also be calculated from measurements of the time required to reach a steady state (Method Ic).

These methods are used for measuring D only for interstitial solute diffusion: the Kirkendall effect complicates any attempt to apply it reliably to substitutional diffusion.

13.2.2 Non-steady-state methods

The change in the concentration distribution in a sample as a result diffusion is measured and D deduced from a solution of Fick's second law [equations (13.2), (13.4), (13.5) or (13.14) appropriate to the conditions of the experiment. There are three common types of experimental arrangement, two of which are usually employed in chemical diffusion coefficient measurements, the third in measurements of tracer diffusion coefficients.

(i) DIFFUSION COUPLE METHOD

Two metals, or two different homogeneous alloys of concentrations c_1 and c_2, are brought into intimate contact across a plane interface, say by welding. Diffusion is allowed to take place by

annealing at a constant temperature for a time t. The distribution of concentration in the sample is then determined in some convenient manner, often by removal and subsequent analysis of a succession of thin layers cut parallel to the initial interface. It is usually arranged that the two halves of the couple be sufficiently thick that the diffusion zone does not extend to either end.

D generally varies with concentration, but no analytic solutions of (13.4) are available so recourse is had to a graphical method of analysis known as the Matano-Boltzmann method. The concentration c is plotted against x and $D(c)$ determined graphically from.

$$D(c)=(2t\cdot\partial c/\partial x)^{-1}\int_{c}^{c_1} x\,\mathrm{d}c \qquad \text{[Method IIa(i)]} \tag{13.15}$$

The origin of x is located by the condition

$$\int_{c_1}^{c_2} x\,\mathrm{d}c=0$$

and this may be shown to coincide, under ideal conditions, with the *initial* position of the interface between the two members of the couple. Thus it is $\tilde{D}$ which is measured in substitutional diffusion. Markers inserted at the interface locate its *final* position after diffusion. It has already been mentioned that measuring their displacement x_m from $x=0$ allows the partial diffusion coefficients to be calculated.

If D varies little in the range c_1 to c_2, and this is often so if the range is sufficiently restricted, equation (13.5) may be used, the solution of which for this case is

$$\frac{c-c_2}{c_1-c_2}=\tfrac{1}{2}\left\{1-erf\left[\frac{x}{2\sqrt{(Dt)}}\right]\right\} \tag{13.16}$$

With $x=0$ defined as before, D can then be calculated directly by a 'least squares' fit of the $c\sim x$ data to this or other appropriate equations [Method IIa(ii)].

Occasionally, the diffusion couple method is used to measure self-diffusion coefficients, one half of the couple being normal metal, the other enriched in one of its active or normal isotopes. It may also be used to measure diffusion coefficients in liquids (Shear-cell method).

With analytic solutions, like (13.16) D can be calculated by measuring c at one position only. This is sometimes done but it is not to be expected that values derived in this way will be as reliable as when derived from a complete $c\sim x$ curve (Method IIb).

The concentration range in a diffusion couple may span any number of phase regions in the equilibrium diagram of the system; the diffusion zone then consists of phase layers with concentration discontinuities across each boundary between two layers. In such cases equation (13.15) [Method IIa(i)] is still applicable. If D is assumed constant, analytic solutions are available and with these it is sometimes possible (Method IIc) to determine D from measurements only of the rates of movement of one or more phase boundaries and knowledge of the equilibrium concentrations at the boundary.[2,3,7]

(ii) IN-DIFFUSION AND OUT-DIFFUSION METHODS

Material is allowed to diffuse into, or out of, an initially homogeneous sample of concentration c_1 under the condition that the concentration at the surface is maintained at a constant and known value c_0 by being exposed to a constant ambient atmosphere. c_1 is usually zero for in-diffusion experiments and so is c_0 for out-diffusion experiments.

D may be calculated from a measurement either of the total amount of material taken up by or lost from the sample (Method IIIb), or of the concentration distribution within the sample after diffusion (Method IIIa). The first method gives an average D over the range c_1 to c_0. For the second, equation (13.15) can be used again to give $D(c)$ or, if D is constant, it may be calculated from an appropriate analytic solution.

When the loss (or gain) of material from the sample entails the movement of a phase boundary, D can again be calculated from the rate of movement (Method IIIc). This method has been mostly used for interstitial solute diffusion, but also occasionally for substitutional diffusion measurements in systems with a sufficiently volatile component. A disadvantage of it is that conditions at the surface may not always be under adequate control so that c_0 is either ill-defined or not constant or both, with consequent uncertainty in D.

A common method of measuring liquid self-diffusion rates employs a type of out-diffusion method. A

capillary tube, closed at one end and containing activated material, is immersed open-end uppermost in a large bath of inactive material. After the diffusion anneal the depleted activity content of the capillary is determined, and D calculated on the assumption that diffusion of the active species out of the tube is subject to zero concentration being maintained at the exit.

For determining the concentration distribution $c(x)$ in any of the above chemical diffusion methods a wide variety of techniques has been employed; these include the traditional methods of chemical and spectrographic analysis, X-ray and electron diffraction, X-ray absorption, microhardness measurements and so forth and the more recent, and often highly sensitive, methods of microprobe analysis, laser and spark source mass spectrometry nuclear reaction analysis and Rutherford back-scattering Also may be mentioned are electrochemical methods where the diffusion sample is contrived as an electrolytic cell wherein diffusion fluxes may be measured as currents and/or surface concentrations as surface potentials. In this edition of the tables the method of analysis is not recorded for it is probably of less importance in assessing the reliability of a result than other features of the experimental procedure.

(iii) THIN LAYER METHODS

These are used now almost exclusively for the measurement of self and of tracer Ds. A very thin layer of radioactive diffusant, of total amount g per unit area, is deposited on a plane surface of the sample, usually by evaporation or electrodeposition. After diffusion for time t the concentration at a distance x from the surface is

$$c(x)=\frac{g}{(\pi Dt)^{1/2}}\exp\left(-\frac{x^2}{4Dt}\right) \tag{13.17}$$

provided the layer thickness is very much less than $(Dt)^{1/2}$. This condition is easy to satisfy because extremely small quantities suffice for studying the diffusion on account of the very high sensitivity of methods of detecting and measuring radioactive substances. For the same reason there is a negligible change in the chemical composition of the sample so D is constant and equation (13.5), of which (13.17), is the solution for this case, is applicable.

After diffusion the activity of each of a series of slices cut from the sample may be determined and D calculated from the slope ($=1/4Dt$) of the linear plot of log activity in each slice against x^2 [Method IVa(i)]. Alternatively, such a plot may be constructed from intensity measurements made on an autoradiograph of a single section cut along or obliquely to the diffusion direction [Method IVa(ii)].

Another method is to calculate D from measurements made, after the removal of each slice, of the residual activity emanating from each newly exposed surface *of the sample.* [Residual activity method; Method IVb.]

Or, D may be determined by comparing the total activity from the surface $x=0$ after diffusion with the original activity at $t=0$ (surface decrease, Method IVc).

Methods IVb and IVc require an integration of equation (13.17). They are generally regarded as less reliable in principle than Method IVa because they obviously necessitate also a knowledge of the absorption characteristics of the radiation concerned. In addition Method IVc is particularly susceptible to errors arising from possible oxidation and from evaporation losses of the deposited material and is rarely used nowadays

A recent development has been the use of the electron-microprobe, and similarly sensitive methods (see above), to measure even impurity diffusion coefficients: instruments are now available with a sensitivity adequate to monitor diffusion from deposited layers of *inactive* diffusant thin enough to meet the requirements for use of equation (13.17) [Method IVa(iii)].

13.2.3 Indirect methods, not based on Fick's laws

In addition to macroscopic diffusion there are a number of other phenomena in solids which depend for their occurrence on the thermally activated motion of atoms. From suitable measurements made on some of these phenomena it is possible to determine a D. The more important of these are:[6,15]

1. Internal friction due to a stress-induced redistribution of atoms in interstitial solution in metals (Snoek effect and Gorsky effect, Method Va.)
2. A similar phenomenon occurring in substitutional solid solution and due, it is believed, to stress-induced changes in short range order (Zener effect, Method Va.)

3. Phenomena associated with nuclear magnetic resonance absorption, especially the 'diffusional narrowing' of resonance lines and a contribution, arising from atomic mobility, to the spin-lattice relaxation time T_1 (Method Vb).
4. Some magnetic relaxation phenomena in ferromagnetic substances (Method Vc).
5. The width of Mössbauer spectrum lines (Method Vod).
6. The intensity and shape of quasi-elastic neutron scattering spectra (Method Ve).

These methods are associated with atomic motion over only a few atomic distances, and so have the advantage of providing measurements of D at temperatures lower than are often practicable by conventional methods. However, some of them are of very limited application. For example, 3, 5, and 6 are obviously limited to diffusion of appropriate nuclei only. Since in every case measurements are made in homogeneous material the diffusion coefficients obtained are of the nature of tracer rather than chemical diffusion coefficients.

Most measurements of D are conducted at a series of temperatures so as to provide values of the constants A and Q occurring in the Arrhenius equation

$$D = A \exp(-Q/RT) \tag{13.18}$$

which usually describes very well the observed temperature dependence.* A is called the 'frequency factor' and Q the activation energy. Wherever possible, experimental measurements are reported in the tables in terms of A and Q alone. Occasionally, accurate measurements, particularly if over an extended temperature range, reveal slightly curved Arrhenius plots. These can usually be well represented by the sum of the Arrhenius terms

$$D = A_1 \exp -Q_1/kT + A_2 \exp -Q_2/kT \tag{13.19}$$

For such measurements A_2 and Q_2 are tabulated immediately below A_1 and Q_1. In Tables 13.3 and 13.4 A_2 and Q_2 are preceded by the signal +. (See e.g. CoGa in Table 13.3.)

Experiments may be made by any of the above methods either with single crystal or polycrystalline material. With polycrystals there is, in addition to diffusion through the grains (volume diffusion), diffusion at a more rapid rate locally through the disordered regions of grain boundaries. This can, however, be reduced to a negligible proportion of the whole by using large grain material and by working at relatively high temperatures because, since $Q_{gb} < Q_v$, grain boundary diffusion rates increase less rapidly with temperature than do volume diffusion rates. Obviously single crystals are to be preferred in accurate measurements of what is intended to be volume diffusion but even in their case there may be, at too low temperatures, a contribution to D from diffusion along dislocations. Measured values of D will then tend to be above the values expected from an extrapolation of the high temperature date using (13.18), and when they do so to a noticeable extent are often discarded in estimating Q and A.

From measurements of the concentration distribution around a grain boundary —usually in a bicrystal into which material diffuses parallel to the boundary—a product $D'\delta$ may be deduced.[12] D' is the coefficient for diffusion *in* the boundary of width δ, δ is an uncertain quantity but all results quoted in Table 13.5 give values for A_{gb} calculated assuming $\delta = 5.0 \times 10^{-8}$cm. $D'\delta$ is found to depend on the orientation of the boundary and on the direction of diffusion within it.

13.3 Mechanisms of diffusion

Most theoretical discussions of diffusion are concerned with an understanding of A and Q rather than of D itself. On the basis of theoretical calculations of Q for various possible mechanisms of diffusion and comparison with observed values, it has been supposed for some time that in metals atoms diffuse substitutionally by thermally activated jumps into vacant lattice sites, i.e. by the 'vacancy mechanism'. This has been very convincingly confirmed, at least for f.c.c. metals, by thermal expansion and quenching experiments. At high temperatures, towards the melting point, there is believed to be a sizeable contribution to D from diffusion by bound divacancy pairs. While the same mechanism is usually thought to operate in most metal structures, there is considerable doubt at present whether this is in fact true for a number of so-called 'anomalous b.c.c. metals'· β-Ti, β-Zr, β-Hf, β-Pr, γ-U and δ-Ce · or at least whether the vacancy mechanism is the only one operating in their case. It is also believed that the noble metals and other low-valent solutes (Group II), plus the later transition elements, may dissolve interstitially, at least in part, and diffuse by an interstitial-type process in the alkali metals, in the high-valent Group III and IV elements and also in the *early*

*This is often true even of $\tilde{D}$, because Q_A and Q_B for the partial diffusion coefficients do not seem to differ very much.

members of each of the transition groups, the lanthanide series and the actinide series of elements. This belief stems from the anomalously very large diffusion rates of these solutes in these solvents.[11,13,14]

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Summary of methods for measuring D

STEADY-STATE METHOD with

I.	(a) Measurement of concentration distribution within the sample or,	Ia
	(b) Average gradient calculated from c_1 and c_2 as deduced from equilibrium data or,	Ib
	(c) Time-delay method (measurement of time to reach steady state)	Ic

NON-STEADY METHODS

II.	*Diffusion couple methods*	
	(a) With determination of $c \sim x$ curve and	
	(i) Use of Matano Boltzmann analysis to give $D(c)$	IIa(i)
	(ii) When it is evident (or assumed) that D is effectively constant, calculation of D from an analytic solution	IIa(ii)
	(iii) When it is evident that D is *not* constant and an analytic solution is used to calculate a D corresponding to each value of c—giving an approximate $D(c)$	IIa(iii)
	(b) D calculated from a single concentration measurement	IIb
	(c) D calculated from an analytic solution, assuming D constant, using measurements of rate of movement of phase boundaries and knowledge of equilibrium concentrations on the boundaries	IIc
III.	*In-diffusion and out-diffusion methods* in-(i) out-(ii)	
	(a) D calculated from $c \sim x$ curves	IIIa
	(b) D calculated from total gain or loss, or rate thereof	IIIb
	(c) D calculated from rate of phase boundary movement	IIIc

IV. *Thin layer methods*
- (a) With measurement of $c \sim x$ curve
 - (i) By sectioning and counting — using radioactive diffusant — IVa(i)
 - (ii) By autoradiography — using radioactive diffusant — IVa(ii)
 - (iii) By electron-microprobe or similarly sensitive method—using non-radioactive diffusant — IVa(iii)
- (b) Residual activity method — using radioactive diffusant — IVb
- (c) Surface decrease method — using radioactive diffusant — IVc

V. *Indirect methods*
- (a) By internal friction — Va
- (b) By nuclear magnetic resonance — Vb
- (c) By ferromagnetic relaxation — Vc
- (d) From Mössbauer line spectra — Vd
- (e) From quasi-elastic neutron scattering — Ve

Notes on the tables

1. All measurements are reported whenever possible in terms of A and Q (see equation 13.18) or of A_1, Q_1, A_2 and Q_2 (equation 13.19). A in $cm^2 s^{-1}$; Q in kJoules mol^{-1} ($kJ\,n_1^{-1}$); ($R = 8.31441\ J\,mol^{-1}K^{-1}$ 1 eV = 96.4846 kJ mol^{-1})
2. The 'temperature range' is the range over which measurements were used to calculate A and Q. Extrapolation too far outside this range may not in some cases give reliable values for D.
3. All alloy concentrations are in atomic percentages unless otherwise stated. Purity of material is as quoted and is presumably in weight percentages, although this is not always stated explicitly in papers.
4. s.c. = single crystals; p.c. = polycrystals.
5. In Table 13.4 a single concentration denotes the concentration at which $D(c)$ was determined. Two concentrations separated by a hyphen denote the range of concentration over which measurements were made. Where this is followed by a single D value, or a single set of A and Q values, it is also the concentration range over which these values are averages.
6. Bold type in Table 13.4. This is used: (1) To indicate the species to which the D's, or A and Q values, refer in cases where there might be ambiguity usually for interstitial solid solutions. Where there is no bold type the data refer to the interdiffusion coefficients of the first two substitutional species. (2) To indicate which component was used in the vapour phase in experiments employing methods I and III.
7. Where several measurements exist an attempt has been made to select what appear to be the most reliable one or two. Mostly these are later measurements and references to earlier work can usually be found by consulting the references quoted.

Table 13.1 SELF-DIFFUSION IN SOLID ELEMENTS

Element	A $cm^2 s^{-1}$	Q $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Group IA					
Li	0.125	53.06	308–451	IVa(i), p.c., normal Li. (~8% Li^6)[1]	1 and 2
	$A_1 = 0.196$ $A_2 = 98$	$Q_1 = 53.7$ $Q_2 = 77.16$	227–451	Vb, p.c., Li^8 diffusion in $Li^{7(d)}$	3
Na	$A_1 = 0.72$ $A_2 = 57 \times 10^{-4}$	$Q_1 = 48.15$ $Q_2 = 35.71$	195–371	IVa(i), p.c., Na^{22}	4
	0.12	41.5	349–371	Vc, s.c. and p.c.	102
K	0.16	39.19	221–335	IVa(i), p.c., K^{42}, 99.97%	5
Rb	0.23	39.4	250–313	Vb, p.c.	6
Group IB					
Cu	$A_1 = 0.13$ $A_2 = 4.5$	$Q_1 = 197.8$ $Q_2 = 237.4$	573–1 334	IVa(i), s.c., Least squares fit to data of references[7]	8
Ag	$A_1 = 0.055$ $A_2 = 15.1$	$Q_1 = 171.1$ $Q_2 = 226.7$	550–1 228	IVa(i), s.c., Least squares fit to data of references[9]	8
Au	$A_1 = 0.025$ $A_2 = 0.83$	$Q_1 = 164.3$ $Q_2 = 212.3$	603–1 333	IVa(i), s.c., Least squares fit to data of references[10]	8
Group IIA					
Be	$\parallel c$ 0.62 $\perp c$ 0.52	165.0 157.4	836–1 343	IVb, s.c., Be[7]	13
Mg	$\parallel c$ 1.0 $\perp c$ 1.5	134.8 136.1	741–908	IVa(i), s.c., Mg^{28}, 99.9+ %	14
	$\parallel c$ 1.78 $\perp c$ 1.75	139.0 138.2	773–903	IVa(i) and b, s.c., Mg^{26}, 99.99%	15
Ca	8.3	161.2	773–1 073	IVb, p.c., Ca^{45}, 99.95%	16

Table 13.1 SELF-DIFFUSION IN SOLID ELEMENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Group IIB					
Zn	∥*c* 0.13	91.7	513–691	IVa(i), s.c., $Zn^{65,69}$, 99.999%	17
	⊥*c* 0.18	96.3			
Cd	∥*c* 0.118	77.92	420–600	IVa(i), s.c., Cd^{109}, 99.999%	18
	⊥*c* 0.183	82.02			
Group IIIA and rare earths					
Y	∥*c* 0.82	252.5	1 173–1 573	IVb, s.c., Y^{91}	19
	⊥*c* 5.2	280.9			
β-La	1.5	188.8	933–1 113	IVa(i), p.c., La^{140}, 99.97%	20
γ-La	0.013	102.6	1 140–1 170	IV(i), p.c., La^{140}	88
	0.11	125.2	1 151–1 183	IVa(i), p.c., La^{140}, 99.85%	89
γ-Ce	0.55	153.2	801–965	IVa(i), p.c., Ce^{141}, 99.9%	21
δ-Ce	0.012	90.0	992–1 044		
β-Pr	0.087	123.1	1 323–1 473	IVa(i), Pr^{142}, p.c., 99.97%	22
Er	∥*c* 3.71	301.66	1 479–1 684	IVa(i), s.c., Er^{169}, 99.91%	23
	⊥*c* 4.51	302.58			
Eu	1.0	144.4	771–1 072	IVa(i), p.c., Eu^{152}, 99.75%	90
β-Gd	0.01	136.9	1 549–1 581	IVa(i), p.c., Gd^{159}, 99.57%	90
α-Yb	0.034	146.79	823–983	IVa(i), p.c., YB^{169}, 99.5%	91
γ-Yb	0.12	121.0	1 031–1 083		
Group IIIB					
Al	1.71	142.4	723–923	IVa(i), Al^{26}, p.c., 99.9%	24
	2.25	144.4	573–923	IVa(i), p.c.	25
	0.137	123.5	298–581[c]	Vb, p.c., 99.999%	27
	0.176	126.4	358–482	Void annealing rate, 99.9999%	28
Ga	$D = 5.3\ 10^{-13}$		282.8	IVa(i), s.c. and p.c., Ga^{72}, 99.9999%	30
	$D = 5.3\ 10^{-13}$		293.0		
	$D = 7.8\ 10^{-13}$		298.0		
	$D = 9.3\ 10^{-13}$		300.5		
	$D = 42\ 10^{-13}$		302.7		
In	∥*c* 2.7	78.3	317–417	IVa(i), s.c., In^{114}, 99.995%	31
	⊥*c* 3.7	78.3			
α-Tl	∥*c* 0.4	95.9	423–498	IVa(i), s.c., Tl^{204}, 99.9+%	32
	⊥*c* 0.4	94.6			
β-Tl	0.42	80.18	513–573	IVa(i), p.c., Tl^{204}, 99.999%	12
Group IVB					
C	0.4–14.1	682[e]	2 458–2 620	IIIb, C^{14}, natural graphite crystals	33
	∥*a* 0.91	657	2 667–3 175	IVb, C^{14}, columnar pyrocarbon	42
Si	1 460	484.4	1 318–1 663	IVa(i), s.c., Si^{31}	34
	154	448.4	1 128–1 448	IVa(iii) (IMS), s.c., Si^{30}	44
Ge	24.8	303	822–1 164	IVa(i), s.c., Ge^{71}, intrinsic Ge	36
	13.6	298	808–1 177	IVa(i), s.c., intrinsic Ge	37
Sn	∥*c* 12.8	108.9	425–500	IVa(i), s.c., Sn^{113}, 99.999%	38
	⊥*c* 21.0	108.4			
	∥*c* 7.7	107.2	433–501	IVa(i), s.c., Sn^{113}, 99.999%	39
	⊥*c* 10.7	105.1			
Pb	0.995	107.4	473–596	IVa(i), s.c., Pb^{210}, 99.9999%	40 and 41
Group VB					
P	$3.6\ 10^{9}$[c]	114.7	295–316 (α-P)	IVa(i), s.c., P^{33}, 99.999%	87
Sb	∥*c* 56	201.0	773–903	IVa(i), s.c., Sb^{124}, 99.9999%	43
	⊥*c* 0.10	149.9			
Bi		*See* footnote *f*			
Group VIB					
S	∥*c* —	~290	353–368[d]	IVa(i), s.c., S^{35}	47
	⊥*c* $2\ 10^{17}$	215.2			
Se	∥*c* 0.2	116	425–488	IVb, s.c., Se^{75}	48
	⊥*c* 100	135			
Te	∥*c* 130	168.52	578–673	IVa(i), s.c., Te^{127m}, 99.9999%	49
	⊥*c* 39.1×10^{2}	195.48			
	∥*c* 0.6	148	496–640	IVa(i), s.c., Te^{127m}	95
	⊥*c* 20	166			

Table 13.1 SELF-DIFFUSION IN SOLID ELEMENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Group IVA					
α-Ti	6.6×10^{-5}	169.1	1 013–1 149	IVb, p.b., Ti^{44}, 99.97%	50
β-Ti	$A_1 = 3.58 \times 10^{-4}$ $A_2 = 1.09$	$Q_1 = 130.6$ $Q_2 = 251.2$	1171 1813	IVa(i), p.c., Ti^{44}, 99.9%	52
	$D = 3.5 \exp[(-39.4 \times 10^3/T) + (1.548\ 10^7/T^2)]$		779–1 128	*IVa(i), p.c., Ti^{44}*, 99.98%	51
α-Zr	See Figure 13.1		506–855	IVa(i), s.c., Zr^{95}, 99.99%	63
β-Zr	$A_1 = 8.5 \times 10^{-5}$ $A_2 = 1.34$	$Q_1 = 115.97$ $Q_2 = 272.98$	1173–2023	IVa(i), p.c., Zr^{95}, 99.94%	53 and 35
α-Hf	$\parallel c$ 0.86 $\perp c$ 0.28	370.1 348.3	1493 1883	IVa(i), s.c., Hf^{181}, Hf + 2.1% Zr	56
β-Hf	1.2×10^{-5}	162.0	2068 2268	IVa(i), p.c., Hf^{181}, 99.99%	96
	1.1×10^{-5}	159.1	2000–2850	IVa(i), p.c. —	97
Group VA					
V	$A_1 = 0.0200$	$Q_2 = 303.9$	1153–2810	IVa(i), s.c./p.c., V^{48}, 99.99%	57 and 11
	0.288 173	334.68 409.27	997–1 815 1815–2 115	IVa(i), s.c., V^{48}, 99.9 + %	98
Nb	$A_1 = 8 \times 10^{-3}$ $A_2 = 3.7$	$Q_1 = 349.6$ $Q_2 = 438.4$	1353–2693	IVa(i), s.c., Nb^{95}, >99.92%	58
Ta	0.124	413.2	1523–2493	IVa(i), Ta^{182}, p.c.	59
	0.21	423.6	1261–2893	IVa(i), Ta^{182}, s.c.	99
Group VIA					
Cr	1 280	441.9	1073–2090	IVa(i), s.c., Cr^{51}, 99.986%	60 and 100
Mo	$A_1 = 0.126$ $A_2 = 139$	$Q_1 = 437.5$ $Q_2 = 549.3$	1363–2723	IVa(i), s.c., Mo^{99}	61
W	$A_1 = 0.04$ $A_2 = 46$	$Q_1 = 526.3$ $Q_2 = 666.1$	1703–3 413	IVa(i), s.c., W^{187}, 99.999%	62

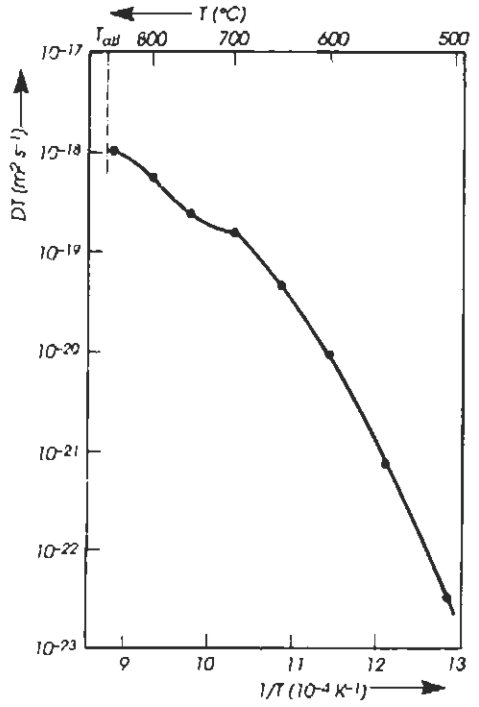


Figure 13.1

Table 13.1 SELF-DIFFUSION IN SOLID ELEMENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Group VIII					
α-Fe	See Figure 13.2[c]		Ferromag	IVa(i), s.c. and p.c.	80 and 92
	118	281.52	1048–1087 (p)	IVb, p.c., Fe^{59}, 99.78%	93
	2.76	250.58	1052–1148 (p)	IVa(i), p.c., Fe^{59}, 99.995%	80
	121	281.6	1067–1169 (p)	IVa(i), p.e., Fe^{59}, 99.98%	71
γ-Fe	0.49	284.12	1443–1634	IVa(i), p.c., Fe^{59}, 99.98%	75
	4.085	311.1	1223–1473	IVc, p.c., Fe^{55}, 99.98%	74
δ-Fe	2.01	240.7	1701–1765	IVa(i), p.c. and s.c., $Fe^{55,59}$	72
	6.8	258.3	1407–1788	IVa(ii' p.c., Fe^{55}, 99.998%	77
Co	0.55	288.5	896–1745	IVa(i), p.e., $Co^{57,60}$, 99.99%	76
	2.54[d]	304	923–1743	IVz(i), s.c., Co^{57}, 99.999%	78
Ir	0.36	438.3	2298–2937	IVa(i), s.c., Ir^{192}	103
Ni	$A_1 = 0.85$ $A_2 = 1350$	$Q_1 = 276.7$ $Q_2 = 400.3$	879–1673	IVa(i) and b, s.c., Ni^{63}. Least squares fit to data of references[79,94]	8
Pd	0.205	266.2	1323–1723	IVa(i), s.c., Pd^{103}, 99.999%	81
Pt	$A_1 = 0.034$ $A_2 = 88.6$	$Q_1 = 254.5$ $Q_2 = 390.6$	773–1998	IVa(i) and c, p.c., Pt^{195m}. Least squares fit to data of refs[82,83,78h]	8
Transuranic elements					
α-Th	395	299.8	963–1183	IVc, p.c., Th^{208}	54
	10^2–5×10^3	347	1373–1673	Vd, s.c., 99.9%	55
β-Th	10^4–10^6	415	1723–1823		
α-U	2×10^{-3}	167.5	853–923	IIa(ii), p.c., enriched U^{234}	64
$D \times 10^{14}$ —	⊥110 ⊥010 001				
	36.7 ≤1.5 42.9		925.9 mosaic		
	19.5 ≤1 19.5		898.5 mosaic	IVa(i), s.c., $U^{233,235}$	65
	6 ≤0.35 7.5		860.4 mosaic		
	3.67 ≤0.35 3.84		587.4 perfect crystal		
β-U	1.35×10^{-2}	175.8	973–1028	IIa(ii), p.c., enriched U^{234}	66
	2.8×10^{-3}	185.1	963–1023	IVb, p.c., U^{235}	67
γ-U[e]	1.19×10^{-3}	111.8	1076–1342	Various. p.c.	68 and 69
	1.1×10^{-4}	150.7	1123–1323[g]	IVb, p.c., 99.76%	70
	0.12	228.2	1103–1353[g]		
ε-Pu	2.2×10^{-2}	77.5	773–895	IIa(ii), p.c., Pu^{240}	85
	4.5×10^{-3}	66.9	765–886	IVa(i), p.c., Pu^{233}	86
δ-Pu	5.32×10^{32}	589	730–750		
δ-Pu	4.5×10^{-3}	99.6	623–713	IIa(ii), p.c., Pu^{238}	84
	0517	126.4	594–715		
γ-Pu	0.38	118.4	484–564	IVa(i), p.c., Pu^{238}	86
β-Pu	$1.69\ 10^{-2}$	108.0	408–454		

Notes:

(*a*) Reference 2 reports measurements of self-diffusion in Li of different isotopic compositions, from which are derived values of D for Li^6 and of Li^7 diffusing in Li^6.

(b) Forced linear fit to slightly curved Arrhenius plot equation 13–19.

(c) Although the higher Q values are confirmed by creep measurements, the indirect methnds indicate lower values of Q at the lower tempertures at which they are applied. Collected results are discussed in references 29.

(*d*) Measures the 'macroscopic diffusion coefficient' D^{SD}. $D_{113,c} = D^{SD} \times f$. f – the correlation factor (~0.5–0.7, depending on T). *See* ref. 3 for details.

(*e*) Assumed in analysis of results that D in direction perpendicular to basal plane is negligible.

(*f*) See reference 45 for account of the highly anomalous self-diffusion behaviour of Bi and reasons for believing the often quoted results of Seith (reference 46) to be very suspect.

(*g*) Orthorhombic S crystals, D_c is 2 to 4 times less than $D_{\perp c}$.

(*h*) The results quoted from (68) are from a least squares fit to the three measurements of reference 69.

(*i*) Samples pre-annealed at diffusion temperature.

(*j*) Samples all pre-annealed at 1080°C.

(*k*) Refs. 80 and 92 give expressions for D over the α range as a function of T and of the magnetization.

(*l*) Measurements with P^{32} (ref. 87) show larger D's due to radiation enhancement from the more energetic P^{32} radiation.

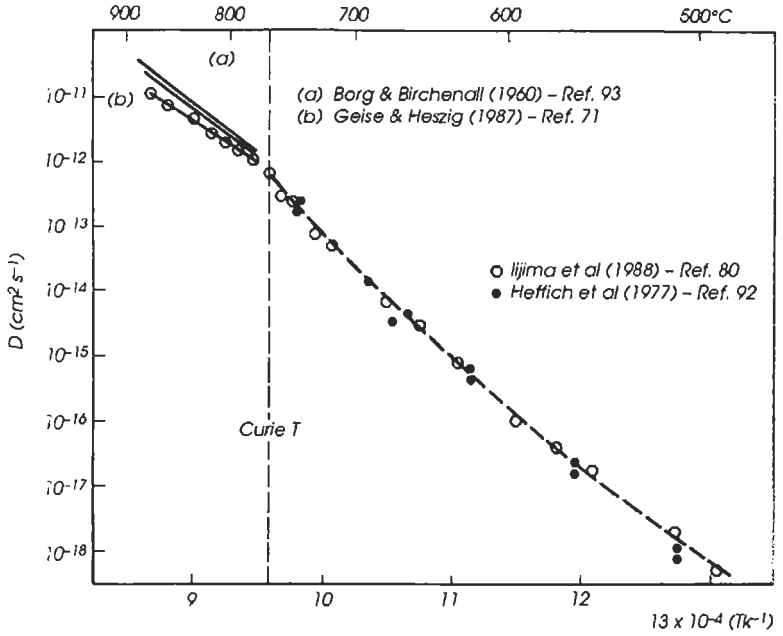


Figure 13.2

(*m*) These values are very close indeed to the values $A=0.5$ $Q=68.0$ previously chosen by Badia (76) as best representing the combined results of a number of other investigations over the range 1050/1400°C.

(*n*) $A=1.27$, $Q=67.2$ are given in reference 76 as the best fit to the combined results of references 79 and 80.

(*o*) Measurements with P^{32} (reference 42) show larger D's due to radiation enhancement from the more energetic P^{32} radiation.

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Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS

In Ay

Element	*A* $cm^2 s^{-1}$	*Q* kJ mol^{-1}	*Temp. range* K	*Method*	*Ref.*
Cu	1.23	193.0	990–1 218	IVa(i), s.c., Cu^{64}, 99.99%	13
	0.029	164.1	699–897	IVa(iii) (SIMS), s.c., 99.99% 258	
Au	0.85	202.1	991–1 198	IVa(i), s.c., Au^{195}, 99.99%	18
Zn	0.54	174.6	916–1 197	IVa(i), s.c., Zn^{65}, 99.99%	14
	0.532	174.6	970–1 225	IVa(i), s.c., Zn^{65}, 9.999%	259
Cd	0.44	174.6	866–1 210	IVa(i), s.c., Cd^{115}, 99.99%	10
Hg	0.079	159.5	926–1 1221	IVa(i), s.c., Hg^{203}, 99.99%	13
Al	0.13	159.5	873–1 223	IIb (X-ray), p.c.,	211
Ga	0.42	162.9	873–1 213	IIb (X-ray), p.c., —	260
In	0.41	170.1	886–1 209	IVa(i), s.c., In^{114}, 99.99%	10
	0.36	169.0	553–838	IVa(i), s.c., In^{114}, 99.999%	261
Tl	0.15	158.7	918–1 073	IVa(i), p.c., Tl^{204}, —	15
Ge	0.084	152.8	943–1 123	IVa(i)m p.c., Ge^{71}, —	15
Sn	0.25	165.0	865–1 1210	IVa(i), s.c., Sn^{113}, 99.99%	10
Pb	0.22	159.5	973–1 098	IVa(i), p.c., Pb^{210}, —	19
As	0.42	149.6	915–1 213	IVa(iii) (EMPA), p.c., 99.98%	107
Sb	0.169	160.4	743–1 215	IVa(i), s.c., Sb^{124}, 99.99%	11
S	1.65	167.5	873–1 173	IVb, s.c., S^{35}, 99.999%	108
Se	0.285	157.4	759–1 109	IVa(i) (ion impl), s.c., Se^{75}, 99.999%	262
Te	0.21	154.7	650–1 169	IVa(i), s.c., Te^{121}, 99.999%	109
Ti	1.33	198	1 051–1 220	IIa(ii) (EMPA), p.c., 99.999%	263
V	2.72	209	1 012–1 218	IVb, p.c., V^{48}, 99.999%	263
Cr	3.29	210	1 023–1 215	IVb, p.c., Cr^{51}, 99.999%	263
	1.07	192.6	976–1 231	IVa(i), s.c., Cr^{51}, 99.9999%	264
Mn	4.29	196	883–1 212	IVb, p.c., Mn^{54}, 99.999%	263
Fe	2.6	205.2	1 073–1 205	IVa(i), s.c., Fe^{59}, 99.999%	106
Ru	180	275.5	1 066–1 219	IVa(i), s.c., $Ru^{103/106}$, 99.99%	12
Co	1.9	204.1	973–1 214	IVa(i), s.c., Co^{60}, 99.999%	106

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Ni	21.9	229.3	1022–1223	IVa(i), s.c., Ni^{63}, 99.99%	16
	15	217.3	903–1200	IVa(i), s.c., Ni^{63},	212
Pd	9.57	237.6	1008–1212	IVa(i), s.c., Pd^{103}, 99.999%	9
Pt	6.0	238.2	923–1223	IIb (X-ray), p.c., —	210
	1.9	235.7	1094–1232	IVa(i), s.c., $Pt^{191/195}$, 99.9999%	265
In Al					
Cu	0.654	136.0	594–928	IVa(i) and b, s.c., Cu^{67}, 99.999%	362
Ag	0.118	116.5	644–928	IVa(i), s.c., Ag^{110}, 99.999%	26
	0.13	117.2	615–883	IVa(i), s.c., Ag^{110}, 99.999%	17
Au	0.131	116.4	642–928	IVa(i), s.c., Au^{198}, 99.999%	26
	0.077	113.0	696 882	IVa(i), s.c., Au^{198}, 99.999%	27
Zn	0.325	117.9	688–928	IVa(i), s.c., Zn^{65}, 99.999%	25 and 26
	0.245	119.6	614–920	IVa(i), p.c., Zn^{65}, 99.99%	131
Cd	1.04	124.3	714–907	IVa(i), s.c., Cd^{115m}, 99.999%	27
Hg	15.3	141.8	718.862	IVb, p.c., Hg^{203}, 99.999%	213
Ga	0.490	123.1	680–926	IVa(i), s.c., Ga72, 99.999%	26
In	0.123	115.6	673–873	IVa(i) and b, p.c., In^{114}, 99.999%	28
	1.16	122.7	715–929	IVa(i), s.c., In^{114}, 99.999%	29
Tl	1.16	152.7	737–862	IVb, p.c., Tl^{204}, 99.999%	213
Si	2.48	137.0	75e3–893	IIa(i) [$D(c\rightarrow 0)$], p.c., 99.999%	215
Ge	0.481	121.3	674–926	IVa(i), Ge^{71}, s.c., 99.999%	26
Sn	0.245	119.3	673–873	IVa(i) and b, p.c., Sn^{113}, 99.999%	28
Pb	50	145.6	777–876	IVb, p.c., Pb^{210}, 99.999%	213
Sb	0.09	121.7	721–893	IVb, p.c., Sb^{124}, 99.995%	130
Li	0.35	126	803–923	Resistometric method, p.c., 99.993%	266
Na	6.7×10^{-4}	97.1	719–863	IVc, p.c., Na^{24}	267
Cs	1.04×10^{-2}	99.2	453–573	IVb, p.c., Cs^{137}, 99.997%	268
Mg	0.0623	115	598–923	IVa(i), s.c., Mg^{28}, 99.999%	215
	1.24	130.4	667–928	IVa(i), s.c., Mg^{28}, 99.999%	214
Zr	728	242	804 913	IVb, p.c., Zr^{95}, 99.999%	215
Cr	1.85×10^3	253.0[a]	859–923	IVa(i), s.c., Cr^{51}, 99.999%	26
Mo	14	250.0	898–928	IIa(ii) EMPA, p.c., 99.99%	269
Mn	104	211.4	730·933	IVa(i), s.c. and p.c., $Mn^{53/56}$, 99.999%	133
Fe	135	192.6	823–913	IVa(i), s.c., Fe^{59}, 99.999%	27
	53	183.4	793–930	IVa(i), p.c., Fe^{59}, 99.995%	134
Co	250	174.6	673–913	IVa(i) and b, p.c., Co^{60}, 99.995%	135
	506	175.7	724–930	IVa(i), s.c., Co^{60}, 99.999%	270 and 26
Ni	4.4	145.8	742–924	Resistometric method, p.c., 99.995%	256
U	0.1	117.2	798–898	IVa(ii), p.c.,U^{235}, 99.995%	132

(*a*) Recalculated values.

In Au					
Cu	0.105	170.2	973 1179	IVa(iii) (EMPA), p.c., 99.99%	17
Ag	0.072	168.3	972· 1281	IVa(i), s.c , Ag^{110}, 99.99%	18
	0.086	169.3	1004· 1323	IVa(i), s.c., $Ag^{101/105}$, 99.999%	271
Zn	0.082	158.1	969–1287	IVa(i), s.c., and p.c., Zn^{65}, 99.999%	272
Hg	0.116	156.5	877–1300	IIIa(i), p.c., Hg^{203}, 99.994%	20
Al	0.052	143.6	773 1223	IIb (X-ray), p.c., —	216
In	0.075	153.7	973–1273	IIa(ii) (EMPA), p.c., 99.999%	110
Ge	0.073	144.5	1010–1287	IVa(i), s.c. and p.c., Ge^{68}, 99.999%	272
Sn	0.0412	143.3	970· 1268	IIa(ii) (EMPA), p.c., 99.999%	110
Sb	0.0114	129.4	1003–1278	IIa(ii) (EMPA), p.c., 99.999%	111
Te	0.063	141.1	909 1145	IVa(i) (ion impl.), s.c., Te^{121}, 99.999%	262
Fe	0.082	174.2	1027–1221	IVb, p.c., Fe^{59}, 99.93%	22
	0.19	172.5	973–323	IIb (X-ray), p.c., —	273
Co	0.22	183.4	973 1323	IIb (X-ray), p.c.,	273
	0.25	185.2	1030–1325	IVa(i), s.c., Co^{57}, 99.999%	274

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS —*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Ni	0.30	192.6	1153–1210	IVa(i), p.c., Ni^{63}, 99.96%	275
	0.25	188.4	973–1323	IIb (X-ray), p.c.,	276
Pd	0.076	195.1	973–1273	IIb (X-ray), p.c., —	277
Pt	7.6	255.0	1173–1329	IVa(i), Pt^{195}, p.c. and s.c., 99.98%	21
	0.095	201.4	973–1273	IIb (X-ray), p.c., —	277
In Be					
Te	$\perp c$ 0.38	198.6	733–1273	Combined $T<677$, IVa(i), Cu^{64}	244
	$\parallel c$ 0.42	193.3	693–1273	data†, s.c. $T<677$, IIa(ii)	217
Ag	6.2	193.0	923–1183	IVb, s.c., Ag^{110}, 99.75%	82
	$\parallel c$ 0.43	164.5	929–1170	IVb, s.c., Ag^{110}, 99.75%	82
	$\perp c$ 1.76	180.9			
Au	$\parallel c$ $D=1.5\times10^{-12}$	938		IIIb(i), s.c., 99.95%	278
	$\perp c$ $D=2.8\times10^{-12}$				
	$\parallel c$ $D=4.4\times10^{-11}$	1053			
	$\perp c$ $D=6.5\times10^{-11}$				
C	3.2×10^{-5}	158.6		IVa(i), p.c., C^{14}	422
Al	1.0	168.3	1068–1356	IVb, p.c., Al^{26}, 99.91%	218
V	29	243	1173–1423	IVb, p.c., V^{48}, 99.7%	219
Nb	2×10^{4}	359.6	1318–1513	IVb, p.c., Nb^{95}, 99.7%	219
Fe	0.53	216.9	973–1349	IVb, p.c., Fe^{59}, 99.75%	82
	1.0	221.9	1073–1373	IIa(i) (EMPA), $D_{Fe\text{-}0.03\%Si}$, p.c.	279
Co	27	287.2	1253–1493	Ib, p.c., Co^{57}, 99.8%	412
Ni	0.2	243	1073–1523	IVb, p.c., Ni^{63}, 99.7%	125
Ce	310	303.5	1223–1513	IVb, p.c., Ce^{141}, 99.7%	219
In Ca					
C	2.7×10^{-3}	97.5	773–1073	IVb, p.c., C^{14}, 99.95%	328
Fe	3.2×10^{-5}	124.8	823–1073	IVb, p.c., Fe^{59}, 99.95%	328
Ni	1.0×10^{-5}	121.0	823–1073	IVc, p.c., Ni^{63}, 99.95%	328
U	1.1×10^{-5}	145.7	773–973	IVb, p.c., U^{235}, 99.95%	328
In Cd					
Ag	$\parallel c$ 1.41	103.2	478–583	IVa(i), s.c., Ag^{110}, 99.999%	129
	$\perp c$ 0.68	105.0			
Au	$\parallel c$ 1.41	106.6	453–578	IVa(i), s.c., Au, 99.9999%	129
	$\perp c$ 3.16	110.7			
Zn	$\parallel c$ 0.13	75.5	428–588	IVa(i), s.c., Zn, 99.999%	129
	$\perp c$ 0.084	75.4			
Hg	$\parallel$ and $\perp c$ 0.212	78.6	432–573	IVa(i), s.c., Hg^{203}, 99.999%	129
In	$\parallel c$ 0.101	73.1	433–573	IVa(i), s.c., In^{114m}, 99.999%	129
	$\perp c$ 0.090	70.9			
Pb	$\parallel c$ 0.060	68.9	514–571	IVa(i), s.c., Pb^{210}, 99.999%	225
	$\perp c$ 0.071	65.8			
In Ce					
Ag	2.5×10^{-2}	88.3	852–969 (γ)	IVa(i), p.c., Ag^{110}, 99.9%	209
	1.2×10^{-1}	92.9	996–1049 (δ)		
Au	4.4×10^{-3}	62.4	823–973 (γ)	IVa(i), p.c., Au^{198}, 99.9%	209
	9.5×10^{-2}	85.8	999–1048 (δ)		
La	3.8×10^{-2}	102.6	998–1048 (δ)	IVa(i), p.c., La^{140}, 99.95%	221
Mn	*See* Figure 13.3[a]		γ and δ range	IVa(i), p.c., Mn^{54}, 99.9%	220
Fe	1.7×10^{-2}	49.8	875–990 (γ)	IVa(i), p.c., Fe^{59}, 99.9%	220
	2.0×10^{-3}	32.2	1005–1046 (δ)		
Co	1.6×10^{-3}	35.6	<1003 (γ)	IVa(i), p.c., ,	280
	1.2×10^{-3}	33.5	1003–1073 (δ)		
Gd	1.2×10^{-2}	100.5	1003–1048 (δ)	IVa(i), p.c., , ···	280

(*a*) No numerical data reported.

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
In Co					
Cu	~1.0	~275	1 158 and 1 273 (f) (Two temps. only)	IIIa(i) (EMPA) (0–5%Cu), p.c., 99.5%	281
Zn	0.12	266.7	1 081–T_c[a]	IVb, s.c., Zn^{65}, —	223
	0.08	254.5	T_c–1 573		
C	8.72×10^{-2}	149.3	723–1 073 (p)	IVa(i)	363
	0.31	153.7	1 073–1 673 (f and p)	IVa(i)	400
S	1.3	226.1	1 423–1 523 (p)	IVb, p.c., S^{35}, 99.99%	282
V	$D = 3.41 \times 10^{-12}$		1 273 (f)	IVb, p.c., V^{48}, 99.9985%	283
[b]	$D = 6.56 \times 10^{-12}$		1 328 (f)		
	$D = 2.46 \times 10^{-11}$		1 388 (f)		
	$D = 9.34 \times 10^{-11}$		1 433 (p)		
	$D = 1.65 \times 10^{-10}$		1 473 (p)		
	$D = 2.39 \times 10^{-10}$		1 523 (p)		
	$D = 3.29 \times 10^{-10}$		1 536 (p)		
Mn	3.15×10^{-2}	232.4	1 133–1 378 (f)	IVb, p.c., Mn^{54}, 99.952%	284
	1.10×10^{-2}	217.7	1 424–1 519 (b)		
Fe	0.11	253.3	1 223–1 643 (p)	IIa(i) (EMPA) [$D(c \rightarrow 0)$], p.c., 99.999%	34, 39 and 43
	0.34	259.6	1 081–T_c (f)	IVb, s.c., Fe^{59}, —	223
	0.16	248.7	T_c–1 573 (p)		
Ni	0.4	282.2	1 409–1 643 (p)	IVa(iii), and IIa(i) [($D(c \rightarrow 0)$] (EMPA), p.c., 99.999%	34
	0.34	269.2	1 045–1 321 (f)	IVb, p.c., Ni^{63}, 99.2%	33
	0.10	252.0	1 465–1 570 (p)		
Pt	0.65	279.3	1 354–1 481 (f and p)	IVb, p.c., Pt^{193m}, 99.99%	222

(*a*) f = ferromagnetic; p = paramagnetic; T_c = Curie temp. of Co (1393 K)
(*b*) Each *D* is the mean of two values.

In Cr

C	8.74×10^{-3}	110.9	423–1 873	$Va_{(150/162\,C)}$ and $IIIa(i)_{(1150/1600\,C)}$	44
V	381	419	1 595–2 041	IVa(i), s.c., V^{48}	417
Mo	2.7×10^{-3}	242.8	1 373–1 693	IVb, p.c., Mo^{99}	46
Fe	0.47	332.0	1 518–1 686	IVb, p.c., Fe^{55}	61

In Cu

Ag	0.61	194.7	873–1 273	IVb, s.c. and p.c., Ag^{110}, 99.99%	228
Au	0.243	197.8	633–1 350	IVa(i), s.c., $Au^{196/198}$, 99.999%	286
Zn	0.34	190.9	878–1 322	IVa(i), s.c., Zn^{65}	1
	0.24	188.8	1 073–1 313	IVa(i), p.c., Zn^{65}, 99.99%	99
Cd	1.2	194.0	983–1 309	IVa(i), p.c., Cd^{115m}, 99.998%	7
	1.27	194.6	1 032–1 346	IVa(i), s.c., Cd^{109}, 99.99%	287
Hg	0.35	184.2	1 053–1 353	IVa(i), s.c., Hg^{203}	2
Ga	0.523	192.7	1 153–1 352	IVa(i), p.c., Ga^{67}, 99.99%	100
In	$A_1 = 0.29$	$Q_2 = 179.6$	602–1 354	IVa(i), s.c. and p.c. Least squares fit to data of 226, 287 and 298	5
	$A_2 = 3\,110$	$Q_2 = 295.4$			
Tl	0.71	181.3	1 058–1 269	IVa(i), s.c., Tl^{204}, 99.999%	36
Si	0.07	171.7	973–1 323	IIb (X-ray), p.c., —	289
Ge	0.315	185.5	1 110–1 326	IVa(i), p.c., Ge^{68}, 99.99%	100
	0.397	187.4	975–1 289	IVa(i), s.c., Ge^{63}, 99.998%	101
Sn	0.842	188.2	1 010–1 321	IVa(i), s.c., $Sn^{mod\,3}$, 99.99%	227
	0.67	184.4	1 018–1 355	IVa(i), p.c., Sn^{113}, 99.999%	290
Pb	0.862	182.4	1 008–1 225	IVa(i), s.c., Pb^{210}, 99.99%	231
P	3.05×10^{-3}	136.1	847–1 319	IVa(i), s.c., P^{32}, 99.999%	291
As	0.202	176.4	1 086–1 348	IVb, p.c., As^{73}, 99.99%	102
Sb	0.34	175.8	873–1 275	IVa(i), s.c., Sb^{124}, 99.99%	8
	0.48	179.5	1 049–1 349	IVa(i), p.c., Sb^{124}, 99.999%	290
Bi	0.766	178.1	1 074–1 348	IVa(i), s.c., Bi^{207}, 99.99%	231
S	23	206.6	1 073–1 273	IVb, s.c., S^{35}, 99.999%	105
Se	10	180.5	878–1 150	IVa(i) (ion impl.), s.c., Se^{75}, 99.999%	262

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*	
Te	0.97	180.5	822–1 214	IVa(i) (ion impl.), s.c., Te^{121}, 99.999%	262	
Be	0.66	195.9	973–1 348	II(b) (X-ray). p.c.	289	
Ti	0.693	196	973–1 283	IIa(i) $[D(c\rightarrow 0)]$, p.c., 99.998%	292	
V	2.48	215	995–1 342	IVb, p.c., V^{48}, 99.998%	103	
Nb	2.04	251.5	1 080–1 179	IVb, p.c., Nb^{95}, 99.999%	104	
Cr	0.337	195	999–1 338	IVb, p.c., Cr^{51}, 99.998%	103	
	1.02	224.0	1 073–1 343	IVb, p.c., Cr^{51}, 99.995%	293	
Mn	0.74	195.5	973–1 348	IIb (X-ray), p.c.	294	
	1.42	204.3	773–976	IVa(i), s.c., Mn^{54}, 99.998%	295	
Fe	1.4	216.9	11 103–1 347	IVa(i), s.c., Fw^{59}, 99.998%	4	
	1.01	213.3	989–1 329	IVa(i), s.c., Fe^{59}, 99.998%	6	
Ru	8.5	257.5	1 221–1 335	IVa(i), s.c., Ru^{103}, 99.999%	229	
Co	$A_1=0.74$ $A_2=736$	$Q_1=217.2$ $Q_2=312.8$	640–1 351	IVa(i), s.c., Co^{60}, 99.998%. Combined data, 4 and 299	5	
W	1.69	225.7	1 163–1 306	IVa(i), p.c., Co^{60}	296	
Rh	3.3	242.8	1 023–1 348	IIb (X-ray). p.c., —	297	
Ir	10.6	276.4	1 183–1 303	IVa(i), s.c., Ir^{192}, 99.99%	230	
Ni	$A_1=0.7$ $A_2=250$	$Q_1=225.0$ $Q_2=299.3$	613–1 349	Fit to data of 4, 99, 300 and 301	5	
Pd	1.71	227.6	1 080–1 329	IVa(i), s.c., Pd^{103}, 99.999%	9	
Pt	0.56	233	1 149–1 352	IVa(i), s.c., $Pt^{191/193}$, 99.999%	265	
In Er						
Au	*See* Figure 13.4[a] $\parallel c$ 15.3 $\perp c$ 23.6		1 270–1 485 (Three *T*s only)	IVa(i), s.c., Au^{198}, 99.91%	285	
C	1.14×10^{-2}	117.2	953–1 473	IVb, p.c., C^{14}	401	
In Fe						
Cu	$D=4.81\times10^{-14}$		963	(α-f)[a]	IVa(iii) (EMPA), s.c., 99.999%	155
	$D=9.55\times10^{-14}$		978			
	$D=1.78\times10^{-13}$		993			
	$D=4.10\times10^{-13}$		1 008			
	$D=8.26\times10^{-13}$		1 024			
	300	283.9	1 045–1 173 (α-p)			
	0.19	272.6	1 198–1 323 (γ)			
	2.86	306.7	1 558–1 641 (γ)	IVa(i), s.c., Cu^{64}, 99.91%	302	
	4.16	305.0	1 378–1 483 (γ)	IVb, p.c., Cu^{64}, 99.96%	303	
Ag	1.95×10^{3}	288.9	1 021–1 161 (α)	IVa(i), p.c., Ag^{110}	158	
	230	278	973–1 033 (α-f)	IVb, p.c., Ag, 99.97%	304	
	38	259.2	1 053–1 173 (α-p)			
Au	$D=9.58\times10^{-14}$		972.1	(α-f)	IVb, p.c., Au^{195}, 99.999%	40
	$D=2.69\times10^{-13}$		997.8			
	$D=5.49\times10^{-13}$		1 012.8			
	$D=1.58\times10^{-12}$		1 034.4			
	31.0	261.2	1 055–1 174 (α-p)			
Zn	60	262.6	1 072–1 169 (α-p)	Ia(iii) (EMPA), s.c.	418	
C	$\text{Log}\,D=-0.9064-0.5199\chi$ $+1.61\times10^{-3}\chi^2$		$\chi=10^4/T$ α-range	Best fit to 83 points from various sources	58	
	0.234	147.8	γ-range	IIa(i) $[D(c\rightarrow 0)]$ $D(\gamma)$ strongly dep. on *T*. *See* Table 13.4	305	
N	$\text{Log}\,D=-1.948-0.4334\chi$ $+6.08\times10^{-4}\chi^2$		$\chi=10^4/T$ α and δ range	Best fit to 52 points from various sources	58	
	0.91	168.56	γ-range	Best fit to points from various sources	306	
P	1.38×10^{5}	332	932–1 057 (α-f)	IVb, p.c., P^{32}	307	
	2.87×10^{2}	271	1 078–1 153 (α-p)			
	6.3×10^{-2}	193.4	1 223–1 573 (γ)	Ib, p.c., P^{32}, 99.99%	308	

(*a*) No values quoted for *A*.

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS *continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
As	4.3	219.8	1 223–1 653 (α)	IIa(ii) (EMPA) (α-stab. 0.5–5% As)	309
	0.58	246.6	1 323–1 573 (γ)	IIa(ii) (EMPA) 0–1.2% As	
Sb	80	269.9	773–873 (α-f)	IIa(ii) ion impl. (NRA)	153
	440	270.0	1 040–1 173 (α-p)	IVb, p.c. and s.c., Sb^{124}	159
Sn	5.4	232.4	973–1 033 (α-f)	IVb, p.c., Sn^{113}	208
	2.4	221.9	1 073–1 183 (α-p)		
	6.1×10^4	316.4	900–1023 (α-f)	IVb, s.c., Sn^{113}	310
	0.845	261.7	1 197–1 653 (γ)	IVa(i), p.c., Sn^{113}, >99.97%	311
S	34.6	231.5	973–1 173 (α)	IVb, p.c., S^{35}, 99.996%	312
	1.7	221.9	1 223–1 523 (γ)	Ib, p.c., S^{35}	150
Be	5.34	218.1	1 073–1 773 (α and β)	IVb, p.c., (α-stabilized-1 wt% Be) 99.9%	148
	0.1	241.2	1 373–1 23 (γ)	IVb, p.c., Be^7, 99.9%	149
Hf	3.6×10^3	407.4	1 371–1 626 (γ)	IVb, p.c., Hf^{181}, 99.98%	151
	9.0×10^4	473.1	1 438–1 593 (γ)	IVb, p.c., Hf^{183}, 99.95%	313
V	124	274	1 058–1 172 (α-p)	IVa(i), p.c., V^{48}, 99.98%	314
	0.62	273.5	1 210–1 607 (γ)		
	0.75	264.2	1 393–1 653 (γ)	IVb, p.c., V^{48}, 99.98%	151
Nb	$D = 1.0 \times 10^{-12}$		993 (α-f)	IVa(i), p.c., Nb, 99.98%	315
	$D = 5.4 \times 10^{-12}$		1 025 (α-f)		
	50.2	252	1 059–1 162 (α-p)		
	0.83	266.5	1 210–1 604 (γ)		
Cr	8.52	250.8	1 070–1 150 (α)	IVb, p.c., Cr^{51}, 99.98%	151
	10.80	291.8	1 233–1 669 (γ)		
	90	271	1 043–1 150 (α-p)	IVa(i), p.c., Cr^{51}	316
Mn	1.49	233.6	973–1033 (α-f)	IVb, p.c., Mn^{54}, 99.97%	152
	0.35	219.8	1 073–1 173 (α-p)		
	0.16	261.7	1 193–1 553 (γ)		
	0.76	224.6	(α and δ)	Combined data 317 [IIa(ii) (EMPA), p.c., 1719/1767 (δ)] and 152	317
Co	7.19	260.4	956–1 000 (α-f)	IVb, s.c., Co^{60}, 99.95%	154
	6.38	257.1	1 081–1 157 (α-p)	IVb, s.c. and p.c., Co^{60}, 99.95%	
	6.38	257.1	1 702–1 794 (δ)	IVa(i), p.c., Co^{60}, 99.95%	
	118	285.9	1 044–1 177 (α-p)	IVb, p.c., Co^{60}, 99.999%	40
	1.0	301.9	1 409–1 633 (γ)	IVa(iii), IIa(ii) (EMPA), p.c., 99.999%	34 and 42
	2.9×10^{-2}	247.4	1 233–1 493 (γ)	IVb, p.c., Co^{60}, 99.9%	318
	See Figure	13.5	785–1 036 (α-f)	IVa(i), s.c., Co^{60}, 99.997%	319 and 320
			1 058–1 164		
	See Figure	13.5	α-f and α-p	IVa(i), p.c., Co^{60}	316
Ni	1.4	245.8	873–953 (α-f)	IVb and c, s.c., Ni^{63}, 99.97%	41
	1.3	234.5	1 083–1 173 (α-p)	IVb, s.c. and p.c., Ni^{63}, 99.97%	
	0.77	280.5	1 203–1 323 (γ)	IVb, s.c., Ni^{63}, 99.97%	
	See Figure	13.6	972–1 032 (α-f)	IVb, p.c., Ni^{63}, 99.999%	90
	9.9	259.2	1 054–1 173 (α-p)		
	3.0	314	1 409–1 673 (γ)	IIa(ii) and IVa(iii) (EMPA), p.c., 99.999%	34 and 364
	See Figure	13.6	788–1 014 (α-f)	IVa(i), p.c., Ni^{63}	321
			1 048–1 160 (α-p)		
	9.7	267.5	1 748–1 767 (δ)	IIa(ii) (EMPA), p.c., 99.96%	361
Pd	0.41	280.9	1 373–1 573 (γ)	Ib, p.c., Pd^{103}, 99.97%	419
Pt	2.7	296	1 233–1 533 (γ)	IVb, p.c., Pt^{193m}	222
U	7×10^{-5}	133.2	1 223–1 348 (γ)	IVa(iii) (fission fragment radiog), p.c.	160

(*a*) α-f = α-phase, ferromagnetic; α-p = α-phase, paramagnetic.

In Hf

Al	170	357	1 023–1 173 (α)	IIa(ii) (ion impl. and NRA). 97% Hf + 3% Zr	323
C	74	312.3	1 393–2 033 (α)	IVb, p.c., C^{14}, Hf + 1.5 wt% Zr	402
	0.8	211.4	2 073–2 373 (β)	IIa(ii), p.c., Hf + 3 wt% Zr	403
Co	5.3×10^{-3}	95.46	1 106–1 798 (α)	IVb, p.c., Co^{60}, 99.99%	235
Cr	0.14	213.9	1 183–2 173 (α and β)	IVb, p.c., Cr^{51}, 99.99%	235

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
In Ho					
C	2.8×10^{-2}	125.6	873–1430	IVb, p.c., ^{14}C	161
In In					
Ag	∥c 0.11 ⊥c 0.52	48.1 53.6	298–423	IVa(i), s.c., Ag^{110m}, 99.99%	94
Au	9×10^{-3}	28.1	298–423	IVa(i), s.c.[a], Au^{198},99.99%	94
Tl	0.049	64.9	323–429	IVa(i), p.c., Tl^{204}, 99.9%	53
Co	1.2×10^{-5}	25.1	383–423	IVa(i), s.c., Co^{60}, 99.997%	380
In K					
Au	1.29×10^{-3}	13.52	279–326	IVa(i), p.c., Au^{195}, 99.95%	123
Na	5.8×10^{-2}	31.19	273–335	IVa(i), p.c., Na^{22}, 99.95%	121
Rb	9.0×10^{-2}	36.76	272–333	IVa(i), p.c., Rb^{86}, 99.95%	124
In La					
Au	2.2×10^{-2}	75.8	873–1073 (β)	IVa(i), p.c., Au^{195}, 99.97%	197
C	4.1×10^{-5}	83.7	723–1128 (β)	IVb, p.c., C^{14}	404
Ce	1.8×10^{-2}	104.7	1139–1170 (γ)	IVa(i), p.c., Ce^{141}, —	156
In Li					
Cu	4.7×10^{-3}	38.6	323–394	IVa(i), p.c., Cu^{64}, 99.98%	113
	0.3	41.87	363–420	IVa(i), p.c., Cu^{64}, 99.98%	324
Ag	0.37	53.72	340–434	IVa(i), p.c., Ag^{110m}, 99.98%	119
	0.54	53.72	323–423	IVa(i), p.c., Ag^{110m}, 99.98%	325
Au[a]	0.21	46.01	319–426	IVa(i), p.c., Au^{195}, 99.95%	118
Zn	0.57	54.34	330–446	IVa(i), p.c., Zn^{65}, 99.98%	117
Cd	0.62	62.80	355–449	IVa(i), p.c., Cd^{115m}, 99.98% 112	
Hg	1.04	59.37	331–447	IVa(i), p.c., Hg^{203}, 99.98%	112
Ga	0.21	54.05	389–447	IVa(i), p.c., Ga^{72}, 99.98%	112
In	0.39	66.44	348–443	IVa(i), p.c., In^{114m}, 99.95%	115
Sn	0.62	66.32[b]	380–447	IVa(i), p.c., —, 99.95%	114
Pb	1.6×10^{4} [b]	105.5	401–443	IVa(i), p.c., —, 99.95%	114
Sb	1.6×10^{12} [b]	173.8	413–449	IVa(i), p.c., —, 99.95%	114
Bi	5.3×10^{14} [b]	198.0	413–450	IVa(i), p.c., —, 99.95%	114
Na (a)	0.41	52.80	325–449	IVa(i), p.c., Na^{22}, 99.8%	116

(*a*) Refs. 326 and 327 report measurements in 95% Li^6 and in 92.5% Li^7. (*b*) Recalculated values.

In Mg					
Ag	∥c 3.62 ⊥c 17.9	133.1 148.2	752–913	IVa(i), s.c., Ag^{110m}, 99.99%	126
Zn	0.41	119.7	740–893	IVa(i), p.c., Zn^{65}, 99.875%	127
Cd	∥c 1.29 ⊥c 0.46	140.7 132.7	733–898	IVa(i), s.c., Cd^{109}, 99.99%	126
In	∥c 1.75 ⊥c 1.88	143.4 142.4	747–906	IVa(i), s.c., In^{114m}, 99.99%	126
C	2.1×10^{-7}	52.3	773–873	IVb, p.c., C^{14}	405
Sn	∥c 4.27 $D_{\perp c}/D_{\parallel c} = 1$ $D_{\perp c}/D_{\parallel c} = 1.13$	149.9	748–903 902.3 858.2	IVa(i), s.c., Sn^{113}, 99.99%	126
Sb	∥c 2.57 ⊥c 3.27	137.3 138.2	781–896	IVa(i), s.c., Sb^{124}, 99.99%	126
Fe	4×10^{-6}	88.8	673–873	IVb, p.c., Fe^{59}, 99.95%	328
Ni	1.2×10^{-5}	95.9	673–873	IVb, p.c., Ni^{63}, 99.95%	328
U	1.6×10^{-5}	95.9	773–893	IVb, p.c., U^{235}, 99.95%	328

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
In Mo					
C	2.0×10^{-3}	115.85	493–543	Via C precipitation rate	389
	1.04×10^{-2}	139	1 533–2 283	IIIb(i), p.c.	388
P	0.19	337	2 273–2 493	IVb, s.c., P^{32}, 99.97%	167
S	32	422.9	2 493–2 743	IVa(iii), s.c., S^{35}, 99.97%	166
	3.4×10^{-2}	297.3	1 238–1 443	IVb, p.c., S^{35}	331
Li	0.01	470.6	1 843–2 243	IIIa(i), s.c. natural Li	330
Y	1.8×10^{-4}	214.8	1 473–1 873	IVb, s.c., Y^{91}, 99.8/99.9%	175
V	2.9	473.1	1 803–1 998	IIa(?) (EMPA), p.c.	332
Nb	14	452.6	2 123–2 623	IVa(i), p.c., Nb^{95}, 99.98%	66
	2.9	569.4	1 998–2 453	IIa(i) (EMPA), p.c.	332
	1.7×10^{-2}	379.3	1 973–2 373	IVb, p.c., Nb^{95}	333
Ta	3.5×10^{-4}	347.5	1 193–1 423	IVb, p.c., Ta^{182}	334
	1.9	473.1	2 098–2 449	IIa(i), p.c.	332
Cr	1.88	342.5	1 273–1 423	—, s.c., Cr^{51}, 99.8%	164
	2.5×10^{-4}	226.1	1 273–1 773	IVb, p.c., Cr^{51}	334
W	1.7	460.5	1 973–2 533	IVa(i) and (ii), p.c., W^{185}	67 and 168
	4.5×10^{-4}	324.5	1 973–2 423	IVb, p.c., W^{185}	334
	140	569.4	2 093–2 453	IIa(i) (EMPA), p.c.	332
Re	9.7×10^{-2}	396.5	1 973–2 373	IVa(i), p.c., Re^{185}	60
Fe	0.15	346.2	1 273–1 623	IVb, p.c., Fe^{59}, 99.96%	232
	3.7×10^{-3}	291.8	1 200–1 478	IVb, p.c., Fe^{59}	331
Co	18	446.7	2 123–2 623	IVa(i), s.c. and p.c., Co^{60}, 99.98%	66
	6	324.5	1 273–1 773	IVb, p.c., Co^{60}	334
Ni	$D = 2.4 - 3.2 \times 10^{-12}$		1 623	IVb, s.c., Ni^{63}	335
U	7.6×10^{-3}	319.9	1 773–2 273	IVb, p.c., U^{235}, 99.98%	165
	1.3×10^{-6}	316.5	2 073–2 373	IV, p.c., U^{235}	57
In Na					
Au	1.5×10^{-2}	21.39	298–351	IVa(i), p.c., Ag^{110}, 99.95%	122
Au	3.34×10^{-4}	9.25	274–350	IVa(i), p.c., Au^{198}, 99.95%	120
Li	Graphical data only		297–353	IVa(i), p.c., Li^{6}, 99.95%	122
K	0.08	35.29	273–365	IVa(i), p.c., K^{42}, 99.95%	121
Rb	0.15	35.55	272–359	IVa(i), p.c., Rb^{86}, 99.95%	121
Cd	0.37	40.86	272–363	IVa(i), p.c., Cd^{115}, 99.95%	122
In	1.79	48.73	293–363	IVa(i), p.c., In^{114}, 99.95%	122
Sn	0.54	43.92	316–363	IVa(i), p.c., In^{113}, 99.95%	122
Tl	0.52	42.62	297–356	IVa(i), p.c., Tl^{204}, 99.95%	122
In Nb					
Cu	$D = 3.71 \times 10^{-10}$		1 829	IVa(i), p.c., Cu^{64}, 99.9%	233
	$D = 1.02 \times 10^{-9}$		1 909		
C	1×10^{-2}	141.92	403–2 613	Combined data from several sources	194
Al	450	430.1	1 700–2 000	IIIb(ii)	176
Sn	0.14	330.3	2 123–2 663	IVa(i), p.c., Sn^{113}, 99.85%	66 and 66a
P	5.1×10^{-2}	215.6	1 573–2 073	IVb, s.c., P^{32}, 99.9%	167
S	2.6×10^{3}	306.0	1 370 × 1 770	IVa(i), s.c. and p.c., S^{35}, 99.6%	177
Y	1.5×10^{-3}	232.8	1 473–1 873	IVb, s.c., Y^{91}, 99.9/99.8%	175
Ti	0.4	370.5	1 898–2 348	IVa(iii) and IIa(i) (EMPA), p.c., 99.9%	169
	9.9×10^{-2}	364.0	1 267–1 765	IVa(i), s.c., Ti^{44}, 99.98%	170
Zr	0.47	364	1 855–2 357	IVa(iii) and IIa(i) (EMPA), p.c., 9.9%	169
	0.85	379.4	1 923–2 523	IVa(i), s.c., Zr^{95}	336
V	0.47	377	1 898–2 348	IVa(iii) and IIa(i) (EMPA), p.c., 99.9%	169
	2.21	355.9	1 273–1 673	IVb, s.c., V^{48}, 99.98%	171
Ta	1.0	415.7	1 376–2 346	IVa(i), s.c., Ta^{182}, 99.76%	173
Cr	0.3	349.6	1 226–1 708	IVa(i), s.c., Cr^{51}, >99.98%	172
	0.13	337.5	1 220–1 766	IVa(i), p.c., Cr^{51}, 99.96%	337
Mo	92	511	1 998–2 455	IVa(iii) and IIa(i) (EMPA), p.c., 99.9%	169
	1.3×10^{-2}	350.4	1 973–2 298	IVb, p.c., Mo^{99}	333

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
W	5×10^{-4}	383.9	2073–2473	IVb, p.c., W^{185}, 99.9%	174
	7×10^{4}	653	2175–2473	IVa(iii) and IIa(i) (EMPA), p.c., 99.8%	169
Fe	1.5	325.3	1663–2373	IVa(ii), p.c., Fe^{55}, 99.74%	68
	0.14	294.3	1663–2168	IVa(i) and (iii), p.c., Fe^{59}, 99.9%	233
Ru	29.3	460.1	2026–2342	Ib, p.c., Ru^{103}, 99.9%	416
Co	4.18×10^{-2}	257.2	1347–2173	IVa(i), s.c., Co^{60}	234
	0.11	274.7	1580–1920	IVa(iii), p.c., Co^{60}, 99.9%	233
	0.74	295.2	1834–2325	IVa(ii), p.c., Co^{60}, 99.74%	68
Ni	9.3	336.6	1261–1519	IVb, p.c., Ni^{63}, 99.82%	338
	7.7×10^{-2}	264.2	1433–2168	IVa(ii) & b, p.c., Ni^{63}, 99.9%	233
U	8.9×10^{-6}	321.5	1773–2273	IVb, p.c., U^{235}, 99.55%	165
In Nd					
Mn	Graphical data only		α and β range	IVa(i), p.c., Mn^{54}, 99.9%	220
	See Figure	13.3			
Fe	4.6×10^{-3}	51.1	α-range	IVa(i), p.c., Fe, 99.9%	220
	1.0×10^{-2}	56.9	β-range		
In Ni					
Cu	0.57	258.3	1327–1632	IVa(i), p.c., Cu^{64}, 99.955%	35
	0.61	255.0	1080–1613	IVa(i) (At. abs. analysis), p.c., 99.95%	340
	0.27	255.5	1048–1323	IVa(iii), s.c., Cu^{64}, 99.999%	45
Ag	8.25	282.2	1123–1323	IVb, s.c., Ag^{110}, 99.99%	341
	8.94	279.4	1297–1693	IVa(i), s.c., $Ag^{110/106}$, 99.98%	237
Au	2.0	272.1	1173–1373	IVa(ii), p.c., Au^{198}, 99.98%	37
Al	1.0	260	914–1212	IVa(iii) (SIMS), s.c., 99.99%	342
In	A_1 1.26	Q_1 = 251.0	777–1659	Least squares fit, data of 238 [IVa(i) s.c., In^{114}, 99.98%] and 343 [IVa(iii) (SIMS), s.c., 99.99%	5
	A_2 1.9×10^{4}	Q_2 = 397.8			
C	0.12	137.3	873–1673	IIa(ii), p.c., C^{14}, 0.1 wt% C	50
Ge	2.1	264.0	939–1675	IVa(i) (ion impl.), s.c., Ge^{69}, 99.99%	344
Sn	4.56	267.2	1242–1642	IVa(i), s.c., Sn^{113}, 99.98%	90
As	1.39	251.8	1239–1634	IVa(i), s.c., As^{73}, 99.98%	345
Sb	3.85	264.0	1203–1674	IVa(i), s.c., Sb^{125}, 99.98%	52
S	1.4	219.0	1078–1495	IVa(i), s.c., S^{35}, 99.98%	236
Te	2.6	254	1135–1553	IVa(i), s.c., Te^{123}, 99.99%	346
Be	1.9×10^{-2}	193.4	1293–1673	IVb, p.c., Be^{7}, 99.9%	147
Hf	1.8[a]	251.0	1023–1423	IIa(ii) (EMPA), p.c., 99.99%	347
V	0.87	278.4	1073–1573	IVb, p.c., V^{48}, 99.99%	143
Cr	1.1	272.6	1373–1541	IVa(i), p.c., Cr^{51}, 99.95%	47
W	2.0	299.4	1373–1568	IVa(i), p.c., W^{185}, 99.95%	59
	2.87	308.1	1346–1668	IVa(i), s.c., W^{181}, 99.98%	49
Fe	1.0	269.4	1478–1669	IVa(i), s.c., Fe^{59}, 99.999%	203
	0.22	252.9	1223–1643	IVb and IIa(i) (EMPA), p.c., 99.999%	34 and 48
Co	0.59	269.6	1123–1643	IVb and IIa(i) (EMPA), p.c., 99.999%	34 and 33
	2.77	285.1	1335–1696	IVa(i), s.c., Co^{57}, 99.98%	49
Pt	2.5	286.8	1354–1481	IVb, p.c., Pt^{193}, 99.99%	222
Ce	0.66	254.6	973–1370	IVa(i), p.c., Ce^{141}, 99.99%	144
Nd	0.44	250.5	973–1373	IVa(i), p.c., Nd^{147}, 99.99%	144
U	1.0	236.1	1248–1348	IVa(ii), p.c., U^{235}, 99.998%	145
Pu	0.64[b]	213.5	1298–1398	IIIa(i), p.c., Pu^{239}(autorad.), 99.997%	146

(*a*) Estimated values.
(*b*) An average value: 146 quotes A 0.14–1.14 $cm^2 s^{-1}$.

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
In Pb					
Cu	7.9×10^{-3}	33.6	498–598	IVa(i), p.c. and s.c., Cu^{64}, —	85
	8.6×10^{-3}	34.2	491–803	IVa(i), s.c., Cu^{64}, 99.9999%	51
Ag	4.6×10^{-2}	60.5	398–598	IVa(i), s.c., Ag^{110}, —	85
	4.8×10^{-2}	60.8	470–750	IVa(i), s.c., Ag^{110}, 99.999%	239 and 348
Au	4.1×10^{-3}	39.1	367–598	IVa(i), s.c., Au^{195}, 99.999%	31
	5.2×10^{-3}	38.6	334–563	IVa(i), s.c., Au^{195}, 99.9999%	349
	5.8×10^{-3}	40.2	441–693	IVa(i), s.c., Au^{195}, 99.9999%	239 and 356
Zn	1.65×10^{-2}	47.8	453–773	IVa(i), s.c., Zn^{65}, 99.9999%	242
Cd	0.409	88.9	423–593	IVa(i), s.c., Cd^{115}, 99.9999%	93
	0.92	92.8	523–823	IVa(i), s.c., Cd^{105}, 99.9999%	350
Hg	1.05	95.0	466–573	IVa(i), s.c., Hg^{203}, 99.9999%	141
	1.5	86.7	523–823	IVa(i), s.c., Hg^{203}, 99.9999%	350
In	33	112.2	437–493	IVa(iii) (EMPA), s.c., 99.999%	139
Tl	0.511	101.9	480–596	IVa(i), p.c., Tl^{204}, 99.99%	32
Sn	0.41	94.4	523–723	IVa(i), s.c., Sn^{113}, 99.9999%	243
	0.29	99.4	468–595	Resistivity method	351
Sb	0.29	92.9	461–588	IVa(i), s.c., Sb^{124}, 99.9999%	140
Bi	$D = 2.66 \times 10^{-10}$		563.4	IVa(i), p.c., Bi, 99.99%	32
	$D = 1.006 \times 10^{-9}$		595.7		
Co	9×10^{-3}	46.4	383–573	IVa(iii) (NRA), p.c., 99.9999%	241
Ni	9.4×10^{-3}	44.5	481–593	IVa(i), s.c., Ni^{63}, 99.9999%	240
	1.1×10^{-2}	45.4	432–523	IVa(i), p.c., Ni^{63}, 99.999%	352
Pd	3.4×10^{-3}	35.4	470–590	IVa(i), s.c., Pd^{109}, 99.9999%	239
Pt	1.1×10^{-2}	42.3	490–593	IVa(i), s.c., (conc. via M.Pt.) 99.9999%	353
Na	6.3	118.5	522–586	IVa(i), s.c., Na^{22}, 99.9999%	354
In Pd					
Fe	0.18	260.0	1373–1523	IVa(i), p.c., Fe^{59}, 99.95%	357
In Pr					
Cu	8.4×10^{-2}	75.8	926–1 059 (α)	IVa(i), p.c., Cu^{64}, 99.9%	199
	5.7×10^{-2}	74.5	1 086–1 187 (β)		
Ag	1.4×10^{-1}	106.3	886–1 040 (α)	IVa(i), p.c., Ag^{110}, 99.93%	200
	3.2×10^{-2}	90.0	1 085–1 195 (β)		
Au	4.3×10^{-2}	82.5	870–1 015 (α)	IVa(i), p.c., Au^{198}, 99.93%	200
	3.3×10^{-2}	84.2	1 075–1 185 (β)		
Zn	$\parallel c$ $D = 4.4 \times 10^{-6}$		1 013 (α)	IVa(i), s.c., Au^{198}, 99.94%	355
	$\perp c$ $D = 3.7 \times 10^{-6}$				
	$\parallel c$ $D = 4.6 \times 10^{-6}$		1 053 (α)		
	$\perp c$ $D = 4.0 \times 10^{-6}$				
Zn	1.8×10^{-1}	103.8	876–1 040 (α)	IVa(i), p.c., Zn^{65}, 99.97%	202
	6.3×10^{-1}	113.0	1 095–1 194 (β)		
In	$D = 3.2 \times 10^{-9}$ (a)		1 039 (α)	IVa(i), p.c., In^{114}, 99.96%	201
	9.6×10^{-2}	121.0	1 075–1 200 (β)		
La	$D = 1.1 \times 10^{-9}$ (a)		1 041 (α)	IVa(i), p.c., La^{140}, 99.96%	201
	1.8×10^{-2}	107.6	1 080–1 190 (β)		
Hb	$D = 3.35 \times 10^{-9}$ (a)		1 004 (α)	IVa(i), p.c., Ho^{166}, 99.96%	201
	9.5×10^{-3}	110.1	1 085–1 180 (β)		
Mn	Graphical data only.		α and β range	IVa(i), p.c., Mn^{54}, 99.9%	220
	See Figure	13.3			
Fe	2.1×10^{-3}	39.4	885–1 060 (α)	IVa(i), p.c., Fe^{59}, 99.9%	220
	4.0×10^{-3}	43.5	1 075–1 180 (β)		
Co	4.7×10^{-2}	68.7	885–1 036 (α)	IVa(i), p.c., Co^{560}, 99.93%	200
	$D = 4.6 \times 10^{-5}$		1 092 (β)		
	$D = 5.0 \times 10^{-5}$		1 151 (β)		

(*a*) Values estimated from graphical data.

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* kJ mol^{-1}	*Temp. range* K	*Method*	*Ref.*
In Pt					
Ag	0.13	258.1	1 473–1 873	IIa(ii) (EMPA), p.c., 99.99%	244
Au	0.13	252.0	850–1 265	IVa(i), s.c., Au^{199}, 99.99%	245
Al	1.3×10^{-3}	193.6	1 373–1 872	IIa(ii) (EMPA), p.c., 99.99%	244
Mn	7.3×10^{-7}	122	1 023–1 223	IVa(i), p.c., Mn^{54}	420
Fe	2.5×10^{-2}	243.4	1 273–1 673	IIa(ii) (EMPA), p.c., 99.99%	244
Co	19.6	310.7	1 023–1 323	IVc, p.c., Co^{60}, 99.99%	204
In Pu					
Cu	1.0×10^{-3}	51.5	773–853 (ε)	IIa(ii), p.c.	247
Ag	$D = 1.08 \times 10^{-10}$		695 (δ)	IVa(i), p.c., Ag^{110m}	247
	4.9×10^{-15}	40.2	772–884 (ε)		
Au	$D = 2.37 \times 10^{-10}$		713 (δ)	IVa(i), p.c., Au^{198}	247
	5.7×10^{-5}	43.1	788–887 (ε)		
Co	1.2×10^{-2}	53.2	617–699 (δ)	IVa(i), p.c., Co^{60}	246
	1.4×10^{-3}	41.4	757–894 (ε)	IVa(i), p.c., Co^{60}	253
In Sc					
C	4.5	205	1 273–1 573	IVb, p.c., C^{14}	423
Fe	$1.5 \times ^{-10}$	54	1 241–1 528 (α)	IIa(ii) (SMLS), p.c., 99.96%	406
	$D = 4.1 \times 10^{-5}$		1 643 (β)		
	$D = 2.6 \times 10^{-5}$		1 702 (β)		
	$D = 3.4 \times 10^{-5}$		1 755 (β)		
	$D = 4.4 \times 10^{-5}$		1 790 (β)		
In Se					
S	$\parallel c$ 1.10×10^{-3}	57.8	333–363	IVb, s.c., S^{35}	205
	$\perp c$ 1.7×10^{-3}	111.0			
Tl	2×10^{-3}	69.5	333–423	IVc, p.c., Tl^{204}	206
In Sm					
C	3.6	146.4	773–1 173 (α)	IVb, p.c., C^{14}	55
In Sn					
Cu	$\parallel c$ $D = 2 \times 10^{-6}$		298	IVa(i), s.c., Cu^{64}	95
	$\perp c$ 2.4×10^{-3}	33.1	413–503		
Ag	$\parallel c$ 7.1×10^{-3}	51.5	408–498	IVa(i), s.c., Ag^{110}	87
	$\perp c$ 0.18	77.0			
Au	$\parallel c$ 5.8×10^{-3}	46.1	408–498	IVa(i), s.c., Au^{198}	87
	$\perp c$ 0.16	74.1			
Zn	$\parallel c$ 1.1×10^{-2}	50.2	408–496	IVa(i), s.c., Zn^{63}, 99.999%	198
	$\perp c$ 8.4	89.2			
Cd	$\parallel c$ 220	118.1	463–498	IVa(i), s.c., Cd^{109}, 999.999%	198
	$\perp c$ 0.18	77.0			
Hg	$\parallel c$ 7.5	105.9	447–499	IVa(i), s.c., Hg^{203}, 99.9999%	136
	$\perp c$ 30	112.2			
In	$\parallel c$ 12.2	107.2	453–494	IVa(i), s.c., In^{114}, 99.998%	30
	$\perp c$ 34.1	108.0			
Tl	1.3×10^{-3}	61.5	410–489	IVa(i) and (ii), p.c., Tl^{204}, 99.999%	138
Sb	$\parallel c$ 7	121.8	466–499	IVa(i), s.c., Sb, 99.999%	198
	$\perp c$ 73	123.1			
Fe	4.8×10^{-4}	51.1	387–462	Vd, p.c., Fe^{57}, 99.9995%	359
Co	5.5	92.1	413–490	IVb, s.c. and p.c., Co^{60}, 99.999%	382
Ni	$\parallel c$ 1.92×10^{-2}	18.1	298–373	IVa(i), s.c., Ni^{63}, 99.999%	365
	$\perp c$ 1.87×10^{-2}	54.2	393–473		

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
In Ta					
Al	1.5	306.2	1 750–2 050	IIIb(ii)	176
C	6.7×10^{-3}	161.6	463–2 953	Combined data, several sources	194
S	0.01	293.1	1 970–2 110	IVb, S^{35}, p.c., 99.0%	162
Y	0.12	302.3	1 473–1 773	IVb, $Y^{91}Y$, s.c., 99.8/99.9%	175
Nb	0.23[a]	413.2	1 194–2 757	IVa(i), Nb^{95}, s.c. and p.c., 99.7%	77
Mo	1.8×10^{-3}	339.1	2 923–2 493	IVb, Mo^{99}, p.c.	358
Fe	0.505	298.9	1 203–1 513	—, —, p.c., —	76
	5.9×10^{-2}	329.9	2 053–2 330	IVa(i), Fe^{59}, p.c.	360
Co	$D = 1.4 \times 10^{-9}$	[b]	2 128	IVa(i), Co^{60}, p.c.	360
	$D = 8.0 \times 10^{-9}$		2 330		
Co	$D = 1.1 \times 10^{-9}$	[b]	2 053	IVa(i), Ni^{60}, p.c.	360
	$D = 1.14 \times 10^{-9}$		2 830		
U	7.6×10^{-5}	353.4	1 873–2 243	IVb, U^{235}, p.c., —	57
	1.03×10^{-6}	117.2	2 186–2 530	IVa(ii) (fission fragment, radiography), nat.U, p.c., 99.9997%	329

(*a*) Average values—Arrhenius plot very slightly curved.
(*b*) Values estimated from graphical representation of results.

In Te

Hg	3.4×10^{-5}	78.3	543–713	IVa(i), p.c., Hg^{203}	81
Sb	$\|c$ 4.6×10^{-2}	147	551–647	IVa(i), s.c., Sb^{122}	410
	$\perp c$ 1.34	165			
Se	2.6×10^{-2}	119.7	593–713	IVa(i), p.c., Se^{75}	81

In Th

α—Thorium					
Fe	5×10^{-3}	80.8	1 238—1 558	IIa(i) (SSMS), p.c., 99.95%	248
Co	5×10^{-4}	55.3	1 238 × 1 558	IIa(ii) (SSMS), p.c., 99.95%	248
Ni	4×10^{-3}	77.9	1 238 × 1 1558	IIa(ii) (SSMS), p.c., 99.95%	248
Pa	1.26×10^{2}	312.8	1 039–1 183	IVa (via α-emission spectra), Pa^{231}, p.c., 99.84%	207
U	2.21×10^{4}	332.0	963–1 150	IVa (via α-emission spectra), U^{233}, p.c., 99.84%	207
β—Thorium					
C	2.2×10^{-2}	113.0	1 713–1 193	IIa(ii), p.c.	407
Zr	1.73×10^{4}	384	1 773–1 873	IIa(ii) (SMLS), p.c., 99.977%	390
Hf	$D = 1.09 \times 10^{-8}$		1 693	IVa(i), p.c., Hf^{181}	391
	$D = 2.09 \times 10^{-7}$		1 963		
V	1.9×10^{-2}	129.8	1 643–1 933	IIa(ii) (SSMS), p.c., 99.95%	249
Nb	0.5	201.8	1 643–1 933	IIa(ii) (SSMS), p.c., 99.95%	249
Ta	0.57	210.6	1 648–1 933	IIa(ii) (SSMS), p.c., 99.95%	249
Mo	15.1	216	1 698–1 873	IIa(ii) (SMLS), p.c., 99.977%	390
W	0.103	160	1 683–1 818	IIa(ii) (SMLS), p.c., 99.977%	390
Re	4.04×10^{-3}	84	1 663–1 943	IIa(ii) (SLMS), p.c., 99.977%	390
Fe	4×10^{-3}	71.6	1 613–1 898	IIa(ii) (SSMS), p.c., 99.95%	248
Co	4×10^{-3}	65.3	1 613–1 898	IIa(ii) (SSMS), p.c., 99.95%	248
Ni	4×10^{-4}	38.1	1 613–1 898	IIa(ii) (SSMS), p.c., 99.95%	248

In Ti

α—Titanium					
Al	9.7×10^{-5}	115.1	973–1 123	"X-ray diff. method", p.c.	366
	7.4×10^{-7}	156.4	873–1 123	IIa(ii) (ion impl.) (N.R.A.), p.c., 99.9%	367
C	7.9×10^{-4}	127.7	873–1 073	IVb, p.c., C^{14}	83
Si	4.4×10^{-7}	105.2	923–1 073	IIIb(i) (ion impl.) (N.R.A.), p.c., 99.9%	368
P	$\|c$ 1.55×10^{-1}	138.2	973–1 123	IVa(i), P^{32}, s.c. For $Ts < 973$, D is < as calc. from D° and Q	369
	$\perp c$ 4.70	172.3			

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Mn	$D = 1.42 \times 10^{-9}$		1 124	IVa(i), Mn^{54}, p.c., 99.998%	370
	$D = 5.21 \times 10^{-10}$		1 072		
	$\parallel c$ 6.0×10^{-1}	189.2	878–1 135	IVa(i), Mn^{54}, s.c., 99.94%	371
	$\perp c$ 4.9×10^{-2}	160.5			
Fe	$\parallel c$ 6.4×10^{-2}	144.2	877–1 136	IVa(i), Fe^{59}, s.c., 99.96%	372
	$\perp c$ 4.7×10^{-3}	112.3			
	1.2×10^{-4}	110.5	973–1 123	IVb, Fe^{59}, p.c., —	373
Co	$D = 6.65 \times 10^{-8}$		1 129	IVa(i), Co^{60}, p.c., 99.998%	370
	$D = 3.64 \times 10^{-8}$		1 072		
	$\parallel c$ 3.2×10^{-2}	126.1	871–1 135	IVa(i), Co^{60}, s.c., 99.96%	374 and 375
	$\perp c$ 1.9×10^{-2}	114.1			
Ni	$D = 2.1 \times 10^{-8}$		1 141	IVa(i), Ni^{63}, p.c., "high purity"	376
	$D = 2.3 \times 10^{-8}$		1 117		
	$D = 7.6 \times 10^{-9}$		1 059		
	$D = 1.8 \times 10^{-9}$		971		
	$D = 6.7 \times 10^{-10}$		912		
	$\parallel c$ 5.4×10^{-2}	141.8	877–1 100	IVa(i), s.c., Ni^{63}, 99.96%	374
	$\perp c$ 5.6×10^{-2}	137.2			
U	4.1×10^{-7}	114.5	1 020–1 124	—, —, —, —	377
β-Titanium					
Cu	$A_1 = 11.3$	$Q_1 = 252$	1 233–1 733	IVa(iii) (EMPA), p.c., "iodide Ti"	88
	$A_2 = 2.1 \times 10^{-3}$	$Q_2 = 122.3$			
Ag	3.0×10^{-3}	180.0	1 213–1 923	IVa(i), p.c., Ag^{110}, 99.95%	84
C	3.2×10^{-3}	79.1	1 223–1 923	IVb, p.c., C^{14}	366
Sn	$A_1 = 9.5$	$Q_1 = 289.7$	1 226–1 868	IVa(i), Sn^{113}, p.c., 99.7%	65
	$A_2 = 3.8 \times 10^{-4}$	$Q_2 = 132.3$			
P	$A_1 = 5.0$	$Q_1 = 236.6$	1 218–1 873	IVa(i), P^{32}, p.c., 99.9%	65
	$A_2 = 3.62 \times 10^{-4}$	$Q_2 = 100.9$			
Be	0.80	168.3	1 188–1 573	IVb, p.c., Be^{7}, 99.62%	187
Sc	4.0×10^{-3}	135.7	1 213–1 843	IVa(i), Sc^{46}, p.c., 99.95%	84 and 65
Zr	4.7×10^{-3}	148.2	1 193–1 773	IVb, Zr^{95}, p.c., 98.94%	70
V	$A_1 = 3.4$	$Q_1 = 257.5$	1 173–1 813	IVa(i), V^{48}, p.c., 99.9%	63 and 65
	$A_2 = 1.0 \times 10^{-3}$	$Q_2 = 145.3$			
Nb	$A_1 = 20$	$Q_1 = 305.6$	1 273–1 923	IVa(ii), Nb^{95}, p.c., 99.7%	64
	$A_2 = 5.0 \times 10^{-3}$	$Q_2 = 164.5$			
Ta	$A_1 = 13$	$Q_1 = 309.8$	1 187–1 873	IVa(i), Ta^{182}, p.c., "iodide Ti"	92
	$A_2 = 3.0 \times 10^{-4}$	$Q_2 = 140.3$			
Cr	$A_1 = 4.9$	$Q_1 = 255.4$	1 243–1 923	IVa(ii), Cr^{51}, p.c., 99.7–99.9%	64
	$A_2 = 5.0 \times 10^{-3}$	$Q_2 = 147.8$			
Mo	$A_1 = 20$	$Q_1 = 305.6$	1 173–1 923	IVa(i), Mo^{99}, p.c., 99.7-99.9%	64
	$A_2 = 8.0 \times 10^{-3}$	$Q_2 = 180.0$			
	0.24	214.8	1 373–1 833	IVb, Mo^{99}, p.c., 99.94%	70
	2.82×10^{-4}	139.0	1 173–1 373		
W	3.6×10^{-3}	183.8	1 173–1 523	IVc, W^{185}, p.c., 98.94%	70
Mn	$A_1 = 4.3$	$Q_1 = 242.8$	1 203–1 923	IVa(i), Mn^{54}, p.c., 99.7%	64
	$A_2 = 6.1 \times 10^{-3}$	$Q_2 = 141.1$			
Fe	$A_1 = 2.7$	$Q_1 = 230.3$	1 193–1 923	IVa(ii), p.c., Fe^{55}, 99.9%	64
	$A_2 = 7.8 \times 10^{-3}$	$Q_2 = 132.3$			
	5.6×10^{-3}	131.0	1 273–1 473	IVb, Fe^{59}, p.c.,	373
Co	$A_1 = 2.0$	$Q_1 = 219.8$	1 183–1 923	IVa(i), p.c., Co, 99.7%	64
	$A_2 = 1.1 \times 10^{-2}$	$Q_2 = 128.1$			
Ni	$A_1 = 2.0$	$Q_1 = 219.8$	1 203–1 923	IVa(ii), Ni^{63}, p.c., 99.7%	64
	$A_2 = 9.2 \times 10^{-3}$	$Q_2 = 123.9$			
U	$A_1 = 2.0 \times 10^{-2}$	$Q_1 = 192.6$	1 173–1 773	, —, —, —	377
	$A_2 = 1.6 \times 10^{-5}$	$Q_2 = 89.2$			
	5.1×10^{-4}	122.7	1 173–1 673	IVb, U^{235}, p.c., 99.62%	195
	2.0×10^{-3}	138.1	1 188–1 298	Ia(ii) (fission fragment, radiography), nat. U, p.c., 99.34%	160
Pu	1.4×10^{-6}	64.1	1 173–1 400	IIa (E.M.P.A. and α-radiography) p.c.3.16	196

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS *continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
In Tl					
Ag	∥c 2.7×10^{-2}	46.9	388–493 (hcp)	IVa(i), s.c., Ag^{110}, 99.9999%	97
	⊥c 3.8×10^{-2}	49.4			
	4.2×10^{-2}	49.8	513–573 (bcc)	IVa(i), p.c., Ag^{110}, 99.9999%	
Ag	∥c 2.0×10^{-5}	11.7	363–493 (hcp)	IVa(i), s.c., Ag^{110}, 99.9999%	97
	⊥c 5.3×10^{-4}	21.8			
	5.2×10^{-4}	25.1	513–573 (bcc)	IVa(i), p.c., Ag^{110}, 99.9999%	
In U					
α—Uranium					
Fe	$D \simeq 3 \times 10^{-10}$		918	via rate of ppt. dissolution, p.c.	381
β—Uranium					
Cr	$D = 3.6 \times 10^{-10}$		943	IVa(i), p.c., Cr^{51}, 99.98	193
	[b] $D = 1.07 \times 10^{-9}$		1013		
	$D = 1.77 \times 10^{-9}$		1021.2	IVa(i), p.c., Cr^{51},	80
Fe	[a] $D = 8.71 \times 10^{-9}$		974	IVa(i), p.c., Fe^{59}, 99.993%	80
	[b] $D = 2.6 \times 10^{-8}$		1033		
Co	1.54×10^{-2}	114.9	964 1036	IVa(i), p.c., Co^{60}, 99.98%	193
γ—Uranium					
Cu	1.96×10^{-3}	100.7	1059 1312	IVa(i), p.c., Cu^{64}, 99.99%	78
Au	4.86×10^{-3}	127.3	1057 1280	IVa(i), p.c., Au^{195}, 99.99%	79
C	0.218	123	1130–1270	IIa(ii), p.c., C^{14}	408
Nb	4.87×10^{-2}	166.0	1063–1376	IVa(i), p.c., Nb^{95}, 99.99%	78
Cr	5.47×10^{-3}	102.4	1070 1311	IVa(i), p.c., Cr^{51}, 99.99%	78
Mn	1.81×10^{-4}	58.1	1060–1212	IVa(i), p.c., Mn^{54}, 99.99%	78
Fe	2.69×10^{-4}	50.3	1059–1263	IVa(i), p.c., Fe^{59}, 99.99%	78
Co	3.51×10^{-4}	52.6	1056–1263	IVa(i), p.c., Co^{60}, 99.99%	78
Ni	5.36×10^{-4}	65.57	1059 1313	IVa(i), p.c., Ni^{63}, 99.99%	78

(*a*) The mean of two values.
(*b*) Values reported at five other *T*s between 943 and 1013, but results too scattered for Arrhenius.

In V					
C	8.8×10^{-3}	116.364	333–2098	Combined data—several sources	38
P	2.45×10^{-2}	208.5	1473 1723	IVb, p.c., P^{32}, 99.98%	163
S	3.1×10^{-2}	142.4	1320–1520	IVb, p.c., S^{35}, 99.8%	162
Ti	0.1	285.0	1373 1623	IVa(i), p.c., Ti^{44}, 99.98%	265 and 383
	34.1	363.9	1623 2076		
Zr	81	369.2	1578 1883	IVa(i), p.c., Zr^{95}, 99.95%	415
Ta	0.244	301.4	1373–2073	IVa(i), p.c., Ta^{182}	251
Cr	9.54×10^{-3}	270.5	1233–1473	IVb, p.c., Cr^{51}, 99.8\5	62
Fe	0.373	297.3	1233 1618	IVa(i), s.c., Fe^{59}	56
	274	385.9	1688–2090		
	2.48	318.7	1473 1823	IVa(i) and (iii), s.c. and p.c., Fe^{59}	384
	31.7	356.6	1823–2088		
Co	1.12	295	1298–2126	IVa(i), s.c., Co^{60}	250
No	0.18	266.24	1175–1948	IVb, s.c. and p.c., Ni^{63}	385
U	1×10^{-4}	257.1	1373–1773	IVb, p.c., U^{235}	57
In W					
C	9.22×10^{-3}	169.1	2073–3073	IIa(ii), p.c., C^{14}	378
	3.15×10^{-3}	172	373–673	Va, p.c.	89
P	26.8	510	2153–2453	IIIa(i), s.c., P^{32}, 99.99%	54
S	2.17×10^{-3}	292.2	2153 × 2453	IVb, s.c., S^{35}	386
Y	6.7×10^{-3}	285.1	1473–1873	IVb, s.c., Y^{91}, 99.8/99.9%	175
Nb	3.01	576.1	1578–2640	IVa(i), s.c. and p.c., Nb^{95}	192
Ta	3.05	585.7	1578–2648	IVa(i), s.c. and p.c., Ta^{182}	192

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
Mo	0.05	506.6	2 273–2 673	IV, p.c., Mo^{99}	191
	0.3	423	1 973–2 373	IVb, p.c., Mo^{99}	334
	1.4	567.3	1 909–2 658	Ia(iii) (SIMS), s.c.	387
Re	275	681.6	2 939–3 501	IVa(i), s.c., $Re^{183/4}$, 99.99%	75
	4.0	597	2 110–2 900	IVa(i), s.c., Re^{186}	190
Fe	0.014	276.3	1 213–1 513	–, p.c., Fe^{59}	76
Os	0.64	538.4	2 105–2 928	IVa(i), s.c., Os^{191}	190
Ir	0.32	506.2	2 007–2 960	IVa(i), s.c., Ir^{192}	190
Ni	$D = 6 \times 10^{-11}$		1 913	IIa(i) (EMPA), p.c.	392
U	2×10^{-3}	433.3	1 973–2 473	IV, p.c., U^{235}	57
	1.8×10^{-2}	389.4	2 245–3 000	IIIb(ii), p.c., 99.99%	186
In Y					
Ag	5.4×10^{-5}	77	1 168–1 453 (α)	IIa(ii), p.c., 99 + %	339
C	1.7×10^{4}	272	1 273–1 733 (α)	IVb and IIa(ii), p.c. Combined data, recalculated	96 and 409
Zr	4.0×10^{-3}	159	1 273–1 573 (α)	IIIa(i), p.c.	411
Fe	1.8×10^{-2}	85	1 173–1 603 (α)	IIa(ii), p.c., 99 + %	339
Co	1.4×10^{-2}	83.3	1 290–1 620 (α)	IIa (LSMS), p.c., 99.6%	413
Ni	5.8×10^{-2}	96.5	1 290–1 580 (α)	IIa (LSMS), p.c., 99.6%	413
In Zn					
Cu	∥c 2.22	123.6	611–688	IVa(i), s.c., Cu^{64}, 99.999%	86
	⊥c 2.00	125.3			
Ag	∥c 0.32	108.9	544–686	IVa(i), s.c., Ag^{110}, 99.999%	23
	⊥c 0.45	115.6			
Au	∥c 0.97	124.3	588–688	IVa(i), s.c., Au^{198}, 99.999%	24
	⊥c 0.29	124.3			
Cd	∥c 0.114	86.0	498–689	IVa(i), s.c., Cd^{115}, 99.999%	24
	⊥c 0.117	85.5			
Hg	∥c 0.056	82.5	533–686	IVa(i), s.c., Hg^{203}, 99.999%	98
	⊥c 0.073	84.5			
Ga	∥c 0.016	77.0	513–676	IVa(i), s.c., Ga^{72}, 99.999%	86
	⊥c 0.018	76.0			
In	∥c 0.062	80.0	444–689	IVa(i), s.c., In^{114}, 99.999%	23
	⊥c 0.14	82.1			
C	1×10^{-5}	50.2	439–656	IVb, p.c., C^{14}	96
Sn	∥c 0.15	81.2	571–673	IVa(i), s.c., Sn^{113}, 99.999%	128
	⊥c 0.13	77.0			
Ni	∥c 8.1	136.6	564–664	IVa(ii), s.c., Ni^{63}, 99.999%	91
	⊥c 0.43	121.5			
In Zr					
α Zirconium					
Cu	c 0.25	154.5	888–1 132	IVa(i), s.c., Cu^{64}, 99.95%	137
	⊥c 0.40	148.7			
Ag	5.1×10^{-3}	187.1	1 037–1 120	IVa(i), p.c., Ag^{110}, 99.99%	254
	∥c 6.7×10^{-4}	173.8	1 063–1 118	IVa(i), s.c., Ag^{110m} 99.999%	257
	⊥c 5.9×10^{-2}	212.4			
Au	$D = 1.3 \times 10^{-11}$		1 113	IVa(i), s.c. (unspec. orientation, Au^{198}, 99.93%	181
Zn	$D = 2.8 \times 10^{-11}$		1 099	IVa(i), s.c. (unspec. orientation), Zn^{65}, 99.93%	181
Al	$D = 3.4 \times 10^{-13}$		1 108	IVa(i), s.c. (unspec. orientation), Al^{26}, 99.93%	376
C	2.0×10^{-3}	151.6	873–1 123	IVb, p.c., C^{14}	188
Sn	1.0×10^{-8}	92.1	'α-phase'	IVb, p.c., Sn^{113}, 99.0–99.9%	71
Sb	$D = 1.4–2.6 \times 10^{-13}$		1 120	IVa(i), s.c. (unspec. orientation), Sb^{122}, 99.93%	376

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS— *continued*

Element	A $cm^2 s^{-1}$	Q $kJ\ mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
S	8.9	185.1	870–1 080	IVa(i), p.c., S^{35}, 99.94%	189
Rb	1.17×10^{2}	255.4	1 033–1 136	IIIb(ii), p.c. (poss. g.b. influence)	186
Be	0.33	133.6	933–1 120	IVa(i) and b, p.c., Be^{7}, 99.99%	255
Ti	$D = 9.4 \times 10^{-13}$		1 116	IVa(i), s.c. (unspec. orientation), Ti^{44}, 99.93%	376
V	1.12×10^{-8}	95.6	873–1 123	IVb, p.c., V^{48}, 99.84%	171
Nb	6.6×10^{-6}	131.9	1 013–1 130	IVb, p.c., Nb^{95}, 99.99%	183
Ta	1.0×10^{2}	293.1	973–1 073	IVb, p.c., Ta^{182}, 99.6%	73
Cr	$\parallel c$ 0.2 $\perp c$ 0.2	162.7 153.3	1 023–1 121	IVa(i), s.c., Cr^{51}, 99.99%	178
Mo	6.22×10^{-8}	103.7	873–1 123	IVb, p.c., Mb^{99}	184
Mn	2.4×10^{-3}	126.4	893–1 083	IVb, p.c., Mn^{54}, 99.5 and 99.999%	179
Fe	$D = 3.7 \times 10^{-8}$ $D = 3.5 \times 10^{-7}$		973 1 071	IVa(i), s.c., Fe^{59}, 99.93%	180
	$D = 7.0 \times 10^{-7}$		1 113	IV (i), s.c. (unspec. orientation), Fe^{59}, 99.93%	376
Co	$\parallel c$ 1.2×10^{3} $\perp c$ 37	183.4 145.8	<873 >923	IVa(i), s.c., Co^{58}, 99.7 and 99.9%	394
	$\parallel c$ 4×10^{4}	191.2	860–990		
Ni	$D = 1.7 \times 10^{-7}$		971		
	$D = 4.0 \times 10^{-7}$		1 023	IVa(i), s.c. (unspec. orientation, Ni^{63}, 99.93%	180
	$D = 9.0 \times 10^{-7}$		1 074		
	$D = 8.0 \times 10^{-7}$		1 103		
	$\perp c$ $D = 1.6 \times 10^{-6}$ $\parallel c$ $D = 6.0 \times 10^{-6}$		1 123	IVa(i), s.c., Ni^{63}	395
Ce	3.5×10^{-7}	106.2	923–1 123	IVb, p.c., Ce^{141}	395
β—Zirconium					
Ag	5.7×10^{-4}	136.9	1 224–1 463	IVa(i) and b, p.c., Ag^{10}, 99.99%	254
	$A_1 = 4.2 \times 10^{-4}$ $A_2 = 190.5$	$Q_1 = 132.3$ $Q_2 = 324.4$	1 199–1 988	IVa(i), p.c., Ag^{110m}	396
C	8.9×10^{-2}	133.1	1 143–1 523	IVb, C^{14}	188
	4.8×10^{-3}	111.8	1 173–1 523	IIa(ii), p.c.	157
Sn	5.0×10^{-3}	163.3	'*β*-phase'	IVb, p.c., Sn^{113}, 99.99.9%	71
P	0.33	139.4	1 223–1 473	IVb, p.c., P^{32}, 99.4%	163
S	27.6	162.4	1 428–1 523	IVa(i), p.c., S^{35}, 99.94%	189
Rb	8.8×10^{-4}	153.7	1 153–1 303	IIIb(ii), p.c.	186
Be	8.33×10^{-2}	130.2	1 188–1 573	IVb, p.c., Be^{7}, 99.7/99.99%	255 and 187
V	7.59×10^{-3}	191.8	1 143–1 473	IVb, p.c., V^{48}, 99.84%	171
	0.32	239.5	1 473–1 673		
	8.9×10^{-5}	116.5	1 166–1 480	IVa(i), p.c., V^{48}, 99.8%	421
Nb	$9 \times 10^{-6} \times (T/1\,136)^{18.1}$	$105.1 + 146.6 \times (T - 1\,136)$	1 155–2 031	IVa(i), p.c., Nb^{95}, 99.94%	69
	7.8×10^{-4}	153.2	1 503–1 908	IVb, p.c., Nb^{95}	397
	1.23×10^{-4}	131.9	1 167–1 433	IVa(i), p.c., Nb^{95}, 99.77%	398
Ta	5.0×10^{-5}	113.0	1 173–1 473	IVb, p.c., Ta^{182}, 99.6%	73
Cr	4.17×10^{-3}	134.0	1 173–1 473	IVb, p.c., Cr^{51}, 99.7%	70
	7.0×10^{-3}	142.3	1 187–1 513	IVa(i), p.c., Cr^{51}, 99.92 99.999%	399
Mo	3.63×10^{-2}	185.9	1 173–1 473	IVb, p.c., Mb^{99}, 99.7%	70
	1.29	243.7	1 628–1 833		
	$A_1 = 1.99 \times 10^{-4}$ $A_2 = 2.63$	$Q_1 = 147.4$ $Q_2 = 285.9$	1 173–1 873	IVb, p.c., Mo^{99}	185
W	0.41	233.6	1 173–1 523	IVc, p.c., W^{185}, 99.7%	70
Mn	5.6×10^{-3}	138.2	1 225–1 420	IVb, p.c., Mn^{54}, 99.5 and 99.999%	179
Fe	9.1×10^{-3}	113.0	1 173–1 673	IVb, p.c., Fe^{59}, 99.7%	70
	7.4×10^{-3}	108	1 176–1 886	IVa(i), p.c., Fe^{59}	74
	$\parallel c$ $D = 2.22 \times 10^{-9}$		765		
	1.75×10^{-8}		834		
	4.70×10^{-8}		871		
	3.70×10^{-7}		934		
	$5.5\ 7.1 \times 10^{-7}$		980.5		
	6.1×10^{-7}		983		

Table 13.2 TRACER IMPURITY DIFFUSION COEFFICIENTS—*continued*

Element	A $cm^2 s^{-1}$	Q $kJ\,mol^{-1}$	*Temp. range* K	*Method*	*Ref.*
	1.68×10^{-6}		1032	IVa(i), s.c., Fe^{59}, 99.98%	414
	2.25×10^{-6}		1093		
	$2.2\text{–}3.6 \times 10^{-6}$		1131		
	2.85×10^{-6}		1133		
	$\perp c$ $D - 1.0 \times 10^{-8}$		871		
	1.2×10^{-7}		980.5		
	3.4×10^{-7}		1032		
	9.9×10^{-7}		1131		
Co	3.26×10^{-3}	91.36	1193–1878	IVa(i), p.c., Co^{60}, 99.99%	182
	3.3×10^{-3}	92	1193–1741	IVa(i), p.c., Co^{57}	74
Ce	$A_1 = 3.16 \times 10^{-2}$	$Q_1 = 173.3$	1153–1873	IVb, p.c., Ce^{141}	185
	$A_2 = 42.17$	$Q_2 = 310.2$			
U	8.15×10^{-5}	111.4	1223–1573	IVb, p.c., U^{235}, 99.61%	408
	$A_1 = 0.36$	$Q_1 = 242.8$	1223–1773	IVa, p.c., U^{235}	72
	$A_2 = 3.0 \times 10^{-6}$	$Q_2 = 82.5$			

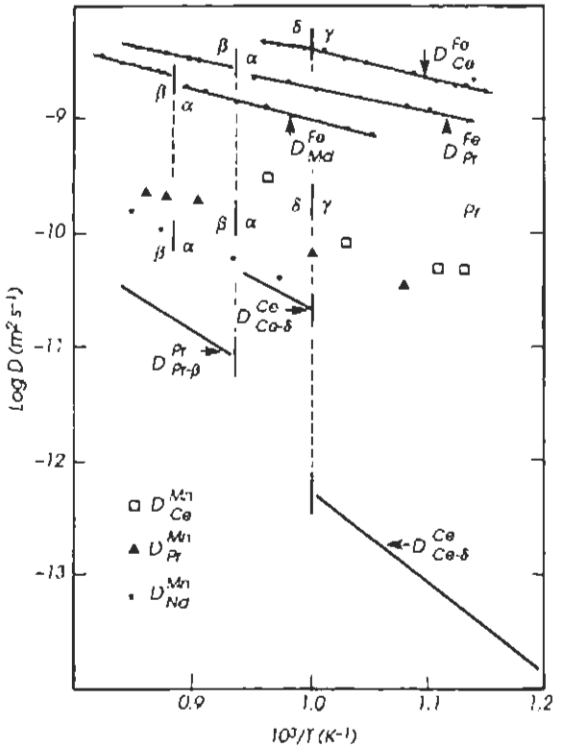


Figure 13.3 *Impurity diffusion of* Fe & Mn *in* CE, Pr & Nd

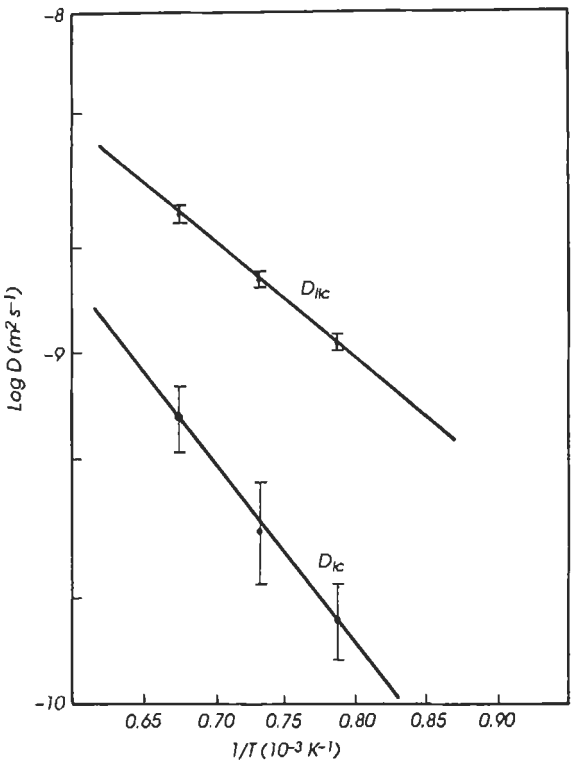


Figure 13.4 *Impurity diffusion of* Au *in* Er

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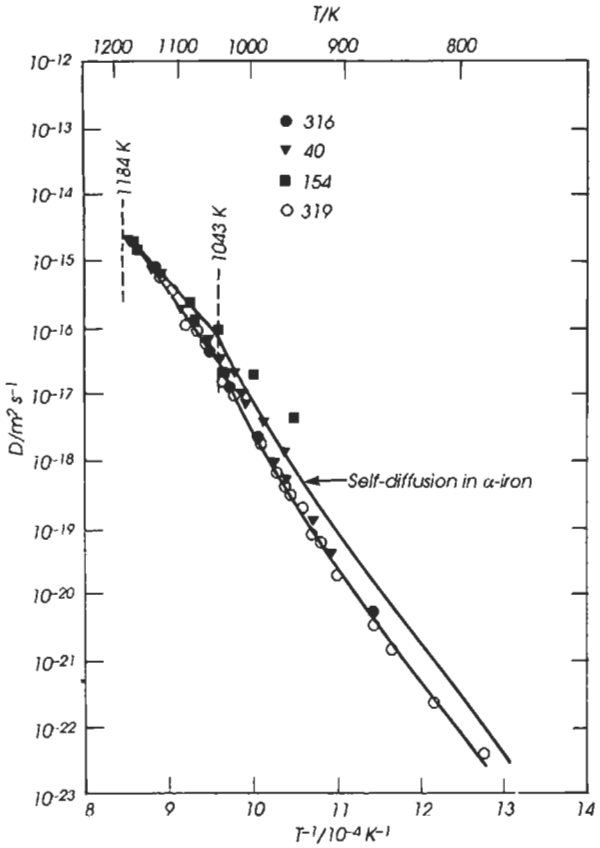


Figure 13.5 *Impurity diffusion of* Co *in* αFe *(replacing 13.2(b))*

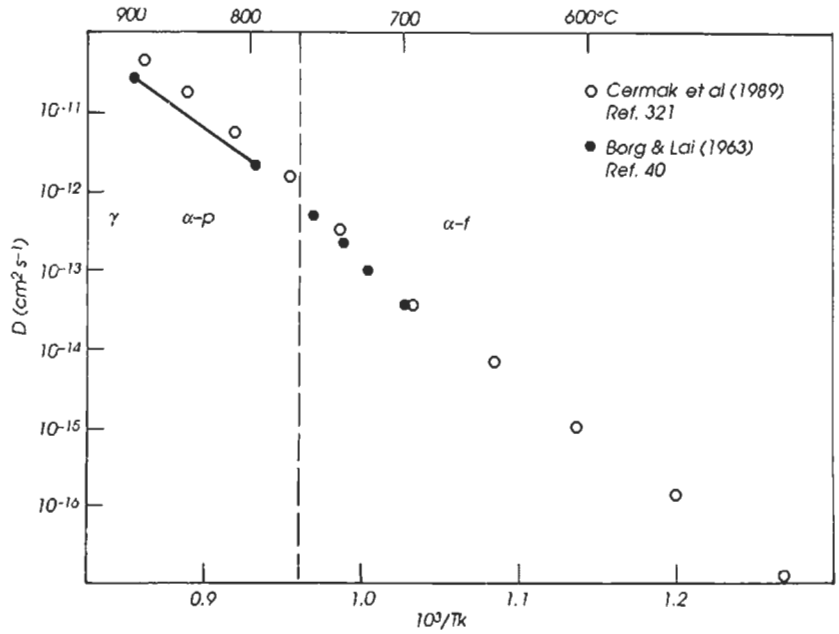


Figure 13.6 *Diffusion of* Ni *in* αFe *(replacing 13.2(a))*

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Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS
Tracer diffusion—Self-diffusion of alloys

Element 1 (*purity*) At.%	*Element 2* (*purity*) At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\ mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\ mol^{-1}$	*Temp. range* K	*Ref.*
Ag	Al						
(—)	(—)		IVa(i)	p.c.			
	2.05	0.25	177.9	—	—	973–1 123	1
	9.47	0.83	179.6	—	—		
	14.1	0.73	172.5		—		
(99.98)	(99.996)		IVc	p.c.			
0–9.4	—	0.39	121.0	(indep. of conc.)		673–868	69
Ag	As						
(5N)	(5N)	IVe (modified), p.c., Ag^{+10}					
—	0–4.15	$b_1 = 57$	$b_2 = 3\,371$		–	909	26
–	0–4.79	−40	−2 901	–	–	954	
–	0–3.49	−33	−2 257	–	–	998	
–	0–3.19	−19	−1 554	–	–	1 073	
Ag	Au						
(99.99)	(99.99)		IVa(i)	s.c.			
100	0	0.49	186.2	0.85	202.1	903–1 283	2
	8	0.52	187.5	0.82	202.2		
	17	0.32	184.4	0.48	198.0		
	35	0.23	182.3	0.35	195.4		
	50	0.19	181.7	0.21	189.6		
	66	0.11	174.7	0.17	186.4		
	83	0.09	171.2	0.12	180.2		
	94	0.072	168.6	0.09	176.2		
0	100	0.072	168.3	0.09	174.6		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Ag	Cd						
(99.99)	(99.999)		IVa(i)	s.c. and p.c.			
100	0	0.44	185.3	0.44	174.9		
	6.50	0.31	178.4	0.33	169.5		
	13.60	0.23	171.5	0.22	161.7	773–1173	3
	27.5	—	—	0.25	150.5		
	28.0	0.16	156.0	—	—		
			IVa(i)	p.c.			
	31		~151	—	~147.4		
	34	—	~151[a]	—	~147.0	833–953	74
	37	—	~151	—	~146.1		
(—)	()	IVa(i), s.c., Ag^{110}					
—	0~3	$b_1 \approx 9.19$				1133	200
		-13.69				1197	
Ag	Cu						
()	(—)		IVa(i)	p.c.			
	1.75	0.66	187.6	—	—		
	4.16	1.84	195.1			973–1163	1
	6.56	0.51	182.1	—	—		
Ag	Ge						
(—)	()		IVb	IVa(i) and		p.c.	
	1.50	0.55	184.2	D_{Ge} greater than for			
	3.00	1.59	189.7	infinite dilution by		973–1123	1
	4.30	1.89	186.3	~15%At.% Ge			and 7
	5.43	2.18	185.1				
Ag	In						
(—)	(—)	IVa(i), s.c., Ag^{110m}					
	0–0.94	$b_1 = 17.6$		—	—	1054	151
(99.99)	(99.99)		IVa(i)	s.c. and p.c.			
100	0	0.44	185.3	0.41	170.8		
	4.40	0.36	178.7		—		
	4.70	—	—	0.45	168.7		
	12.40	—	—	0.57	160.7	773–1173	3
	12.60	0.12	156.6				
	16.60	—	—	0.57	153.3		
	16.70	0.18	151.9	—	—		
Ag	Mg						
(99.95)	(99.95)		IVb	p.c.			
	45.8	1.53	172.9		—		
	49.8	0.28	170.0	—	—	773–973	12
	52.0	0.134	159.1	—	—		
(99.98)	(99.9+)		IVa(i)	p.c.			
	41.10	0.095	139.0	—	—		
	43.60	0.15	147.8	—	—		
	48.48	0.37	165.4	—	—	773–973	13
	48.72	0.39	166.2	—	—		
	52.82	0.33	153.7	—	—		
	57.15	0.051	120.2			773–873	
	60.88	$D_R^* = 4.37 \times 10^{-9}$ at 773.5 K					
Ag	Pb						
(—)	(—)		IVa(i)	p.c.			
	0.21	0.22	177.9	—	—		
	0.25	—	—	0.22	158.3		
	0.52	—	—	0.38	162.0		
	0.71	0.89	187.1	—	—	973–1073	9
	1.30	0.70	182.1	—	—		and 1
	1.32	—	—	0.46	161.2		
()	(99.9999)		IVa(i)	s.c.			
0.09	—	$D_{Ag}^*/D_{Ag(Pb}^*$	= 1.115	(b = 136.8)	1257.3		63
0.18			= 1.25				

(a) Activation energies read from graph in Reference 74.

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* kJ mol^{-1}	A_2^* $cm^2 s^{-1}$	Q_2^* kJ mol^{-1}	*Temp. range* K	*Ref.*
Ag	Pd						
('Spec. Pure')			IVa(i)	p.c.			
	0–21.8	$027e^{-n.2c}$	183.0	—[b]	—	988–1 215	4
	0–20.4	—[b]	—	$12.5e^{-7.5c}$	239.5	1 123–1 173	5
Ag	Sb						
(99.99)	(99.99)		IVa(i)	s.c.			
	0.53	0.38	182.1	(c)			
	0.89	0.30	179.4	"	—	823–1 173	6
	1.42	0.275	175.8	—	—		
(5N)	(5N)	IVa(i), p.c., Ag^{110m}					
	0–6.5		*See* Figure 13.7			890–1 048	204
Ag	Sn						
(—)	(—)			p.c.			
	0.18	0.13	174.6	—			
	0.48	0.13	171.2	"	—		24
	0.91	0.17	169.6	"	—		
	0.97	0.28	165.0	—	—	973–1 123	25
	2.8	0.1	161.6	"	—		
	4.56	0.23	166.2	—	—		24
	5.1	0.2	161.6	—	—		25
	7.45	0.16	154.9	—	—		
()	(—)		p.c. IVb	Ag^{110m}, Sn^{113}			
75	25	1.03×10^{-3}	93.8	4.01×10^{-4}	95.5	473–673	128
(—)	(—)		p.c. and s.c. IVa	Sn^{113}, Ag^{110}			
100	~0	1.0	191.3	0.17	160.8		
	1.7	—	—	0.125	156.8		
	0.108	0.13	172.9	—	—		
	0.8	0.12	168.3	—	—	893–1 073	129
	3.0	0.085	160.8	—			
	4.7	0.07	157.0	—	—		
	6.0	0.07	154.9	—			
()	()	IVa(i), s.c., Ag^{110m}					
—	0–0.77	$b_1 = 20.2$		—	—	~1 052	151
(5N)	(5N)	IVb, p.c., Ag^{110m}					
				$10^{10} D_{Ag}^*$			
		946 K	989 K	1 041 K	1 108 K	1 145 K	
—	0	0.237	0.666	2.47	8.51	16.6	
—	0.948	—	—	2.77	—	"	
	0.963	—	—	—	"	17.6	
—	1.41	—	"	—	10.4	—	
—	1.44	0.373	0.990	"	—	—	
"	2.35	"	—	3.06	—	"	
"	2.54	"	—	"	—	25.6	
	2.62	0.540	1.46	—		—	
—	3.0	—	"	—	16.1	—	
	3.06	"	—	4.33	"	—	170
"	3.47	—	—	—	—	31.0	
—	4.32	—	—	"	19.6	"	
	4.33	0.880	2.48	—		—	
—	4.48	—	—		—	42.4	
—	4.49	"	—	6.57	"	—	
—	5.71		—	—	30.6	—	
—	6.60	1.77	5.01	—	"	—	
—	7.04	"	—	—	41.1	—	
"	7.71	—		15.4	—	"	
—	8.67	3.36	7.32	—	"	—	

(*b*) c – conc. of Pd.
(*c*) In 0.7 At.% Sb alloys, D_{Sb}^* same as D in pure Ag.
In At.% Sb alloys, D_{Sb}^* ~20% greater than D in pure Ag.

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A_1^\dagger$ $cm^2 s^{-1}$	$Q_1^\dagger$ $kJ\,mol^{-1}$	$A_2^\ddagger$ $cm^2 s^{-1}$	$Q_2^\ddagger$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Ag	Tl						
(—)	(—)		IVa(i) and IVb p.c.				
100	0	0.724	190.5	0.15	158.7		
	1.1	0.42	182.1	0.72	169.1	913–1 073	7
	2.6	0.35	175.4	0.57	165.0		
	5.5	0.10	157.4	—	—		
Ag	Zn						
(99.999)	(99.999)		IVa(i)	s.c.			
0.00	—‖*c*	0.31	109.3	0.13	91.7		71 and
	⊥*c*	0.45	115.6	0.18	96.3		23 of
0.35	—‖*c*	—	—	—	—		Table 2
	—⊥*c*	0.49	115.8	—	—		
0.57	—‖*c*	—	—	0.14	91.9		
	⊥*c*	—	—	0.22	96.8		
0.68	—‖*c*	0.35	109.2	—	—	593–688	70
	⊥*c*	—	—	—	—		
0.89	—‖*c*	0.42	110.1	—	—		
	⊥*c*	0.69	117.3	—	—		
1.40	—‖*c*	—	—	0.17	92.4		
	⊥*c*	—	—	0.26	96.8		
(99.999)	(99.999)		IVa(i)	s.c.			
—	0	$D_1 = 1.43 \times 10^{-10}$		—	—	1 020	
		$= 17.2 \times 10^{-10}$		—	—	1 153	
—	1.10	$= 1.63 \times 10^{-10}$		—	—	1 020	
		$= 19.9 \times 10^{-10}$		—	—	1 153	
—	2.08	$= 1.80 \times 10^{-10}$		—	—	1 020	
		$= 21.8 \times 10^{-10}$		—	—	1 153	
—	3.10	$= 2.0 \times 10^{-10}$		—	—	1 020	
		$= 24.1 \times 10^{-10}$		—	—	1 153	
—	4.05	$= 2.28 \times 10^{-10}$		—	—	1 020	
		$= 26.2 \times 10^{-10}$		—	—	1 153	
(99.99)	(99.999)		IVa(i)	p.c.			
85	15		~150.7	0.11	150.7		10
70	30	0.29	150.7	0.46	147.4	773–973	8
(Merck.)	(99.999)		IIb	p.c.			
52.4	47.6	4.55×10^{-3}	73.7	—	—	673–883	11
Al	Au						
(5N)	(5N)		Vb, p.c., Al^{27}				
1.5	—	7×10^{-3}	135	—	—		
3.0	—	1.3×10^{-3}	123.5	—	—	550–1 150	112
5.0	—	3×10^{-4}	106	—	—		
Al	Co						
(99.9)	(Carbonyl)		IVc	p.c.			
	10	—	—	2.65	282.6	1 313–1 493	14
42	—	—	—	1.84×10^2	355.9	1 273–1 473	
49	—	—	—	333×10^2	427.1	1 373–1 573	15
50.7	—	—	—	0.013×10^2	272.1	1 273–1 473	
	49/57		Individual D_{Co}* values plotted at 1 250				16
Al	Cu						
(99.999)	(—)		IVa(i)	s.c.			
—	1.0	—	—		$D = 4.02 \times 10^{-10}$	762	72
					$D = 7.92 \times 10^{-9}$	881	
()	()		IVb	p.c.			
0	—	—	—	0.43	203.1		
2.80	—	—	—	0.46	201.0		
5.50	—	—	—	0.30	196.8	1 073–1 313	73
8.83	—	—	—	0.46	197.2		
11.7	—	—	—	0.61	197.6		
14.5	—	—	—	4.2	213.9		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* kJ mol^{-1}	A_2^* $cm^2 s^{-1}$	Q_2^* kJ mol^{-1}	*Temp. range* K	*Ref.*
(99.994)	()		Vb	p.c.			
—	0	0.10	127.7	—	—	~603–733	127
	0.15	6×10^{-4}	100.9	—	—		
Al	Cu						
()	()		Vb, p.c., Al^{27}	—	—	750–1 030	190
(99.99)	(99.99)	IVa(i), p.c., Zn^{65}		Diff. of Zn			
—	0			0.16	116.9	714–894	
—	0.69			0.13	115.2	714–894	
—	1.23	$D^*_{Zn}(c_i) = D^*_{Zn}(o)(1 + B_i^{Zn} c_i)$		0.28	120.0	714–872	41
—	1.57			0.33	120.9	754–855	
—	1.86	$B^{Zn}_{Cu} = 13.3$ (Av. value)		0.67	125.2	779–844	
Al	Cu	Zn					
(99.99)	(99.99)	(99.99)	IVa(i), p.c., Zn^{65}	Diff. of Zn			
	0	2.04		0.18	116.9	714–894	
—	0.69	2.04	$B^{Zn}_{Zn} = 9.6$ (Av.	0.20	116.9	714–854	
—	1.23	2.04	values)	0.17	115.5	714–872	41
—	1.57	2.04	$B^{Zn}_{Cu} = 11.7$	0.20	116.3	754–855	
—	1.86	2.04		0.38	120.2	779–844	
Al	Fe						
(—)	(—)		IVa	p.c.			
		Diff. of Co					
3.47	—	0.1	221.9	3.2	247.0		
7.95		1.9	234.5	4.5	251.2		
13.5		6.8	144.9	0.4	217.7		
20.6	—	22.0	251.2	32.0	263.8		
23.6	—	27.0	251.2	27.0	261.7	—	17
35.5		210.0	280.5	—	—		
42.0	—	580.0	297.3	—	—		
47.3		6 300.0	330.8	—	—		
52.0	—	148.p	280.5	60.0	276.3		
Al	Fe						
(4N)	(4N)		IVb, p.c., Fe^{59}				
6	—	—	—	0.42	197.7	1 088–1 478 (p)	
10	—	—	—	0.06	195.9	765–941 (f)	
10	—	—	—	0.02	183.5	1 156–1 450 (p)	197
18		—		0.01	197.7	816–953 (f)	
18	—	—	—	0.01	171.5	973–1 450 (p)	
(α phase)				p = paramagnetic,		f = ferromagnetic	
()	()		IVb	p.c.			
5.7	—	—	—	3.7	245.8	1 123–1 458	75
()	()		IVa(i)	p.c.			
'$AlFe_3$'		1.74×10^2	211.4	Individual Re		823–903	
'AlFe'		8.5×10^{-5}	105.1	diffusion coefficients		823–903	76
Al_2Fe		3.99×10^3	232.4	are reported in		793–903	
Al_3Fe		8.9×10^{-4}	117.2	reference 77		823–873	
Al	Li						
()	()	Vb, p.c., Li^7					
50 (β)	50	—	—	2.63×10^{-6}	10.2	100–400	111
()	()	Vb, p.c., Li^7					
51.7	48.3	—	—	2.54×10^{-5}	12.4	300–368	
50.6	49.4	—	—	1.56×10^{-6}	11.7	300–368	
50.0	50.0	—	—	8.34×10^{-6}	10.9	300–473	
48.1	51.9	—	—	2.34×10^{-6}	9.2	300–368	
46.9	53.1	—	—	2.58×10^{-7}	8.4	300–419	

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A_1^{\dagger}$ $cm^2 s^{-1}$	$Q_1^{\dagger}$ $kJ\,mol^{-1}$	$A_2^{\ddagger}$ $cm^2 s^{-1}$	$Q_2^{\ddagger}$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Al	Ll In						
45	50 5	—	—	9.26×10^{-6}	11.1	300–353	150
Al	Li Ag						
48	50 2	—	—	1.66×10^{-6}	8.88	300–368	
47	50 3	—	—	3.63×10^{-7}	6.95	300–419	
Al	Mg						
(99.994)	()		Vb	p.c.			
	0	0.10	127.7	—	—	~603–733	127
	2.2	0.93	128.1	—	—		
	5.5	0.21	116.0	—	—		
Al	Ni						
(—)	(—)		IVc	p.c.			
		Diff. of Co^{60}					
—	47.3	47×10^{-2}	237.0	—	—	1 323–1 623	18
—	48.5	9.3×10^{-2}	250.8	—	—		
—	49.4	4.4×10^{-3}	219.8	—	—		
—	50.7	57.7	337.5	—	—		
—	53.1	2.6	283.0	—	—		
—	55.1	7.2×10^{-3}	197.2	—	—		
()	()	IVb, p.c., Ni^{63}					
24	—	—	—	132	345	965–1 625	30
				$+1.1 \times 10^{-7}$	134.8		
25	(Ni_3Al)	—	—	146	347		
				$+1.1 \times 10^{-7}$	141.1		
				105	342		
				$+2.0 \times 10^{-8}$	121.8		
()	()		IVb	p.c.			
		Diff. of In^{114m}					
—	48.3	—	—	1.2×10^{-4}	177.9	1 273–1 623	78 and 130
—	48.6	1.29×10^{-3}	237.0	1.04×10^{-3}	209.8		
—	49.0	—	—	53×10^{-4}	200.5		
—	49.2	—	—	0.23	275.9		
—	50.0	3.98×10^{-3}	242.8	4.461	307.3		
—	53.2	—	—	0.63	274.2		
—	54.5	—	—	0.15	250.4		
—	58.0	1.83×10^{-4}	170.0	0.035	216.5		
—	58.5	—	—	0.096	253.7		
—	58.7	—	—	0.725	250.4		
—	73.20	—	—	3.11	300.3	1 173–1 573	106
—	74.71	—	—	1.00	303.1		
—	76.20	—	—	4.41	306.3		
Al	Ni Ti						
()	() ()						
19.92	— 5.13	—	—	0.055	262.79	1 173–1 573	106
20.83	— 5.01	—	—	0.039	259.7		
21.84	— 5.13	—	—	0.085	266.9		
Al	Si						
(99.99)	(99.99)	IVa(i), p.c., Zn^{65}		Diff. of Zn			
—	0			0.26	119.1	673–837	41
—	0.05	$B_{Cu}^{Zn} = 23$ (Av. value)		0.23	118.2		
—	0.10			0.30	119.5		
—	0.15	(*See* Al Cu for definition)		0.32	120.2		
—	0.20			0.29	119.8		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Al	Si	Zn					
(99.99)	(99.99)	(99.99)	IVa(i), p.c., Zn^{65}	Diff. of Zn			
—	0	1.48		0.21	116.9		
—	0.05	1.48		0.37	120.6		
—	0.10	1.48	$B_{Si}^{Zn}=9$ (Av. value)	0.40	121.1		
—	0.15	1.48		0.29	119.1		
—	0.20	1.48		0.33	119.6		
—	0	2.13		0.31	119.4	673–837	41
—	0.05	2.13	$B_{Si}^{Zn}=30$ (Av. value)	0.21	116.7		
—	0.10	2.13		0.26	118.1		
—	0.15	2.13		0.43	121.2		
—	0.20	2.13	$B_{Zn}^{Zn}=7.5$ (Av. value)	0.29	118.9		
Al	Zn						
(99.99)	(99.99)		IVa(i)	p.c.	Zn^{65}		
	0	—	—	0.27	120.4		
	1.16	—	—	0.25	119.0		
(At.%)	1.73	—	—	0.18	116.7		
	2.15	—	—	0.22	117.6	613–893	149
	2.80	—	—	0.22	117.1		
	3.29	—	—	0.24	117.5		
	3.76	—	—	0.23	116.9		
()	()	IVb, p.c., Zn^{65}					
—	7.06	—	—	0.170	112.46		
—	15.17	—	—	0.324	113.17		
—	24.24	—	—	0.209	108.27		
—	31.27	—	—	0.288	105.67		
—	41.51	—	—	0.229	103.54		
—	52.52	—	—	0.162	100.53	585–782	19
—	53.28	—	—	0.575	106.64		
—	55.04	—	—	0.692	108.10		
—	56.85	—	—	1.514	111.87		
—	57.28	—	—	0.575	106.81		
—	57.50	—	—	1.35	111.41		
(4N5)	()	IVa(i), p.c., Zn^{65}					
—	20	—	—	0.25	109	621–783	
—	28.9	—	—	0.22	105	588–611	
—	40	—	—	0.17	101	632–714	198
—	50	—	—	0.23	100	558–611	
—	58.5	—	—	0.036	91	528–611	
(99.994)	()		Vb	p.c.			
	0	0.10	127.7	—	—		
	8	0.087	122.7	—	—	~613–733	127
	11.5	0.035	117.2	—	—		
	18.8	0.025	113.5	—	—		
Al	Zn	Mg					
(99.99)	(99.99)	()	IVVa(i)	p.c.	Zn^{65}		
	0	1.11	0.34	121.5			
	0.71	1.12	0.25	119.2			
	1.49	1.13	0.23	118.0			
	2.11	1.14	0.31	119.5			
(At.%	0	2.77	0.24	119.0			
	0.71	2.80	0.27	119.0	688–848	149	
	1.48	2.83	0.21	116.8			
	2.11	2.86	0.17	115.1			
	0	4.43	0.28	118.6			
	0	6.63	0.50	121.1			

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Au	Cd						
(99.99)	(99.95)		IVa(i)	s.c.			
50	50	0.17	116.8	0.23	117.2	573–863[a]	20
(99.999+)	(99.999+)		IVa(i)	s.c.			
	47.5	0.23	117.6	1.36	129.8	623–873	21
	49.0	0.61	125.6	1.50	130.6	713–823	
	50.5	0.12	109.7	0.22	113.5	713–823	
Au	Cu						
()	()		IVc	p.c.			
25	75	6.5×10^{-3}	159.9	—	—	823–1 173 (Disord.)	81
		Diffusion of Co^{57}					
25	75	4.2×10^{-2}	192.6			923–1 173	89
(5N)	(5N)		IVa(i), p.c., Cu^{64}, Au^{195}				
		$10^{10} D^*_{Au}$		$10^{10} D^*_{Cu}$			
1.25	–	1.7		1.83			
2.5	–	1.8		2.03			
5.0	–	2.08		2.48			
7.48	–	2.40		3.02		1 133	174
12.44	–	3.08		4.18			
14.25	–	3.36		4.62			
17.43	–	3.88		5.88			
Au	Ni						
(99.96)	(99.9)		IVa(ii)	p.c.	IVa(i)		
100	0	0.26	189.7	0.30	192.6		
	10	–	—	0.80	199.3		
	20	0.05	168.3	0.82	200.1	Variable	
	35	—	—	1.10	205.6	For Ni,	32(Au)
	36		—	1.10	205.6	323–348	
	50	0.091	181.7	0.09	186.3	temp.	
	65	0.51	204.3	0.005	165.8	ranges	23(Ni)
	80	1.1	253.3	0.05	206.0	only)	
	90	—	—	0.04	213.9		
0		2.0	272.1	0.40	267.1	—	
Au	Pb						
()	(99.999 9)		IVa(i)	s.c.			
0.04	—	$D^*_{Pb}/D^*_{Pure\,Pb} = 2.2$		($b_1 = 5726$)		472.4	
0.015	–		=0.55				
0.04	–		=1.6				
			=1.75[a]	($b_1 = 4\,312$)		488.2	63
0.06	–		=2.85				
0.08	–		=3.8				
			=4.05[a]				

(*a*) Between 863 K and the m.p. at 899 K there is marked upward curvature in the Arrhenius Plot.

(*a*) Samples pre-annealed before diffusion.

Au	Zn						
()	()		IVa(i)	s.c.			
–	49	0.19	133.6	0.84	144.9	701–923 (Ordered β')	79
–	50	0.33	138.6	1.93	148.2		
–	51	0.016	113.0	0.047	115.1		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Be	Ni						
()	()		IVb	p.c.			
—	1.68	—	—	0.41	247.0	1 173–1 373	80
—	7.9	—	—	0.23	188.4		
C	Cr Fe						
	() ()		IVb	p.c.			
	0.5	45×10^{-3}	111.0	—	—	1 673–1 873	85
	1.0	20×10^{-3}	100.5	—	—		
C	Cr Ta						
()	() ()		IVb	p.c.			
—	— 1.0	5×10^{-3}	120.6	—	—	1 573–1 773	85
Ce	Fe						
(—)	(—)		IVa(i)	p.c.			
0		—	—	0.44	280.5	1 273–1 573	28
1.15		—	—	0.052	247.0		
2.46		—	—	0.015	226.1		
3.39		—	—	0.021	226.1		
4.97		—	—	0.029	225.2		
6.21		—	—	0.050	225.2		
Cu	Fe Ni						
(—)	(—) (—)		IVb	p.c.			
c%	(γ) 20	–	–	$18.10^{-0.92c}$	314–25c	1 073–1 573	29
c%	25	–	–	$71.10^{-0.65c}$	330.8–21c	1 323–1 603	

(a) These values also represemt the best fit to the original (reference 26) and later measurements when plotted altogether. *See* reference 27.

C	Fe Si						
	(99.97)	V(a)	p.c.				
0.104	(α) 5.5	D_C^* 'virtually' the same as im Si-free Fe				26–70	67
Cd	Cu						
()	(99.998)						
0–1.8	—	—	—	$b_1 = 35$	$b_2 = 1\,400$	1 076	109
Cd	Mg						
(—)	(—)		IVb	s.c.			
75	25	11.2×10^{-5}	51.9 (Ord.)	—	—	327–363	31
75	25	0.074	69.9 (Disord.)	—	—	368–473	
25	75	4.10^{-5}	68.2 (Ord.)	—	—	393–428	32
25	75	1.2×10^{-6}	53.6 (Disord.)	—	—	428–554	
Cd	Pb						
()	(99.999 9)		IVa(i)	s.c.			
			Effect of Cd on D_{Pb}^*				
		(*See* eq. 13.9a)	b_1	b_2	b_3		
			45.197	438.1	—	472	
0 to 5			30.028	407.7	44 286	521	52
			19.138	1 070.2	—	574	
Cd	Pb						
(6N)	(6N)	IVa(i), p.c., Cd					
0–0.022	—	$B_1 = -1\,200$				470.7	180

With increasing Cd conc. D_{Cd}^* initially decreases and then beyond 0.022% monotonically increases.

(5N)	(5N)	Diff. of Ni	IVa(i), p.c., Ni^{63}			
0	—	$10^5 D = 2.04$				
0.37	—	= 1.88				
0.86	—	= 1.73				
1.01	—	= 1.58	—	—	506.7	186
1.36	—	= 1.56				
2.64	—	= 1.17				
3.66	—	= 1.02				

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%		A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Co	Cr			IVb	p.c.			
(—)	(—)							
	4		0.67	275.5	—	—	1 373–1 623	33
	7		56.3	332.0	—	—		
Co	Cr	Ni		IVb	p.c.			
()	(—)	(—)						
	9	26	6.3	301.9		—	1 373–1 623	33
	18	26	0.4	268.8	—	—		
Co	Cu	Si						
(99.99)	(99.99)	()		IVa(i), p.c., Co^{58}				
0–2 68		0.54		$B_1 \simeq -9$			1 325	158
Co	Fe			IVa(i)	p.c.			
()	()		1.33	290.6	1.26	286.8	1 285–1 437(γ)	34
50	50		2.0	251.2	0.25	230.3	1 068–1218(α)	
				556.8		556.8	928–995(CsCl)	
()	()			IVb	p.c.			
—	21		0.54	272.1	—	—	1 373–1 573	33
()	()			IVa(iii)	p.c.			
	0			Diffusion of Ni $D_{Ni} = 13.10^{-12}$				
	30.2			= 11.5				
—	68.5			≈8–8.8			1 409	82
—	88.3			−5				
—	100			=6				
()	()			IVb	p.c.	(F ≈ Ferromagnetic)		
0	(bcc)		1.83	234.0	—		1 073–1 172	107
	(fcc)		0.77)	265.0		—	1 223–1 633	
3	(bcc)		9.17	266.3	—	—	903–1 023(F)	
6.8	(bcc)		0.469	187.1	—	—	903–1 073(F)	
			5.72×10^{-5}	146.5	—	—	1 153–1 193	
	(fcc)		0.109	326.2	—	—	1 283–1 583	
28.6	(bcc)		1.25×10^{-3}	198.0		—	903–1 093(F)	
	(fcc)		3.36×10^{-2}	266.3	—	—	1 333–1 583	
49.6	(bcc)		6.59×10^{-2}	247.0	—	—	1 023–1 123(F)	
	(fcc)		0.154	349.6	—	—	1 333–1 583	
67.2	(bcc)		6.04×10^{-3}	190.9	—	—	903–1 153(F)	
	(fcc)		3.15×10^{-2}	265.0	—	—	1 333–1 583	
89.6	(fcc)		6.44×10^{-2}	251.2	—	—	1 073–1 283(F)	
			1.61×10^{-2}	234.0	—	—	1 333–1 153	
100	(fcc)		0.50	273.8	—	—	1 045–1 321(F)	
			0.17	260.4	—	—	1 465–1 570	
(99 8)	(99.9)		IVb	p.c.	Co^{60}			
0			0.029	247.4	—	—		
8			20.54	321.5	—	—		
10			15.65	369.0	—	—	1 233–1 493	131
15			1.98	289.7	—	—		
20			0.31	261.7	—	—		
Co	Fe							
()	()		IVb, s.c., Fe^{59}					
	6		—	—	0.58	273.3	1 081–T_c	
	6		—	—	0.15	261.7	T_c–1 573	176
	10		—	—	0.68	279.3	1 081–T_c	
—	10		—	—	0.18	263.3	T_c–1 573	
Co	Fe	Ti						
()	()	()		IVb	p.c.			
	15	4	0.008	214.4	—	—	1 373–1 473	33
Co	Fe	V						
()	()	()		IVa(i), p.c. Co^{60}				
60	15	25	10.5	313[a]	—	—	1 277–1 570	152

(a) Reports Ds below T_c but these scattered and affected by g.b. diffusion.

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A_{\perp}^{*}$ $cm^2 s^{-1}$	$Q_{\perp}^{*}$ $kJ\,mol^{-1}$	$A_{\parallel}^{*}$ $cm^2 s^{-1}$	$Q_{\parallel}^{*}$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Co	Ga						
(5N)	(5N)		IVa(i), p.c., Co^{60}, Ga^{72}				
48.6		2.0×10^3	311.6	2.7×10^3	319.4	1 248 × 1 353	
52.4	—	2.7×10^3	310.7	1.3×10^2	309.7	1 256–1 386	175
54.3	—	2.0×10^3	305.9	1.5×10^3	307.8	1 250–1 340	
57.2	—	2.0×10^2	275.9	1.4×10^2	275.9	1 193–1 345	
()	()		IVa(i), p.c., Co^{60}, Ga^{67}				
45.2	—	1.91	247	766×10^3	326	651–1 100	
		[a] $+4.68 \times 10^3$	326	+0			
48	—	2.10×10^{-3}	209	554	308	700–1 150	
		$+1.5 \times 10^3$	308	$+2.65 \times 10^9$	494		
50	—	0.379	245	220	301	639–1 150	132
		+878	301	$+8.11 \times 10^6$	417		
56	—	1.02	235	475	303	625–1 150	
		$+1.60 \times 10^3$	303	$+2.30 \times 10^7$	430		
60	—	0.303	216	80.8	281	600–1 150	
		+343	281	$+1.99 \times 10^6$	395		
Co	Mn						
()	()	IVb	p.c.	Mn^{54}			
100	~0	—	—	3.15×10^{-2}	232.4	1 133–T_c	
		—	—	1.1×10^{-2}	217.7	T_c–1 519	
—	5.22	—	—	1.38	268.4	1 141–T_c	133
		—	—	0.501	256.7	T_c–1 473	
—	10.24	—	—	1.36	263.3	1 176–1 421	
Co	Nb Zr						
()	() ()			IVa(i), p.c., Co^{57}			
2	31 —	1.8	194	—	—	1 125–1 645	156
Co	Ni						
(99.5)	(99.98)		IVb	p.c.		Ferromag.[a]	
100	0	0.5	273.8	0.34	269.2	1 045–1 321	
	11	0.61	280.9	0.46	274.7	1 137–1 321	
	20	5.96	307.7	1.66	291.8	1 118–1 321	
	30	1.16	287.2	2.01	286.8	1 045–1 172	
	51	0.096	257.5	0.36	266.3	974–1 072	
						Paramag.[a]	35
100	0	0.17	260.4	0.10	252.0	1 465–1 570	
	11	0.21	266.3	0.17	262.5	1 417–1 570	
	20	2.42	297.3	0.41	275.1	1 363–1 519	
	30	0.78	280.5	0.67	271.3	1 323–1 523	
	51	0.12	252.0	0.21	253.7	363–1 463	
	100	0.75	270.9	1.70	285.1	973–1 463	
(99.4) [a] [b]	(99.8)		IVb	p.c.			
99.5	—	1.66	287.6	3.35	297.3	1 320–1 584(O) 1 493–1 693(Ni)	
93.8		7.4	305.2	5.40	302.3	1 483–1 643	
89.0		2.52	290.1	6.42	304.0		
80.6		0.99	275.9	1.89	285.5	1 433–1 683	
72.6		0.70	270.5	1.60	281.4		
49.4		0.18	250.4	0.25	61.1	1 373–1 623	
43.3		0.52	262.1	0.69	267.1		83
21.1		0.33	255.8	0.45	262.1	1 433–1 683	
10.8		0.66	263.8	1.47	276.3		
4.3		0.49	261.3	2.86	284.7	1 483–1 643	
0.03		1.11	271.7	1.39	275.9	1 423–1 663	
()	()		IVb	p.c.			
		Diffusion of Fe^{59}					
50	50	125	320.3			1 273–1 523	84
	(99.4%)	Diffusion of C^{14}			IVb	p.c.	
5.25		0.4	154.9	—	—	873–1 173	36

(*a*) According to reference 64 measurements in pure Co, in Co + 11% Ni and Co + 20% Ni alloys do not convincingly demonstrate a difference in A^* and Q^* values for the paramagnetic and ferromagnetic regions.
(*b*) All alloys contain 0.1–0.2 Mg.

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%		A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Co	Mn	Ni						
()	()	()		IVb	p.c.			
19.5	20.3	60.0	0.86	253.3	—	—	1 293–1 393	14
40.6	20.45	38.9	0.22	240.7	—	—	1 293–1 433	
59.7	20.6	19.5	0.05	228.2	—	—	1 333–1 433	
Co	Ti							
(99.97)	(99.97)			IVa(i)	p.c.			
1.6			—	—	1.26×10^{-3}	145.3	1 233–1 777	121
3.3			—	—	1.58×10^{-3}	140.3	1 166–1 617	
4.9			—	—	1.41×10^{-2}	160.4	1 076–1 573	
7.4			—	—	2.50×10^{-2}	162.9	1 076–1 484	
Co	Ti							
(99.9)	(99.8)		IVa(i), p.c., Co^{60}					
—	21.5		4.3×10^{-2}	203	—	—	1 074–1 323	199
(Co_3Ti)	22.8		1.2×10^{-2}	188	—	—		
—	24.0		3.7×10^{-3}	174	—	—		
Co	Zr							
()	()			IVa(i)	p.c.			
			$D^*_{Co\ in\ pure\ Zr}$		$D^*_{Zr}/D^*_{Pure\ Zr}$			
0.395	-		0.900		0.948			
0.747	—		—		1.322 8			
1.22	—		0.861		1.668		1 266	118
1.61					2.143 3			
1.995	—		0.820		2.223 9			
Cr	Fe							
(99.9)	(99.9)			IVb	p.c.			
9.13					9.27	230.7	548–999(Ferro.α)	86
			—	—	0.42	219.4	1 050–1 098(Para.α)	
			—	—	0.12	237.4	1 173–1 313	87
15.22					1.25	226.5	868–950(Ferro.α)	86
				—	0.27	215.6	999–1 050(Para.α)	
19.75				—	0.65	217.3	848–919(Ferro.α)	
					0.18	208.1	963–1 098(Para.α)	
()	()			IVb	p.c.			
2			3.21	244.5				
6			1.21	237.4	—	—		
13			0.64	231.9	—	—	1 073–1 673	37
16			0.19	218.1	—	—		
19			0.18	216.9	—			
15	2.0		238.6			—		88
()	()			IVb	p.c.	Fe^{59}		
0			—	—	4.4	253.3		
0.87	(wt.%)		—		4.3	252.9		
1.43			—		4.2	252.5		
3.09			—		4.0	251.6	Paramag.	134
5.05			—	—	3.7	250.0	α phase	
6.68			—	—	3.6	249.1		
8.18			—	—	3.3	247.9		
11.93					2.9	244.9		
99.997)	(99.997)		Diff. of S		IVb, p.c. S^{35}			
18			0.166	184				
26 wt.%			3.06×10^{-2}	171			1 123–1 473	164
34	—		6.18×10^{-2}	177				
(99.9)	(99.9)				IVb, p.c., Cr^{51}, Fe^{59}			
0	—		1.16	276.7	0.72	278.7		
0.93	—		1.30	286.0	—	—		
1.53			—	—	0.73	283.1		
3.31			0.35	273.8			1 223–1 473	192
5.4					0.41	276.4		
7.2			0.13	261.6	—	—		
8.8	—		—	—	0.069	257.1		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%		$A_1^{\uparrow}$ $cm^2 s^{-1}$	$Q_1^{\uparrow}$ $kJ\,mol^{-1}$	$A_2^{\uparrow}$ $cm^2 s^{-1}$	$Q_2^{\uparrow}$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
(≥98)	(≥98)							
26			0.156	202.6	—		1 223–1 593	38
51			40.0	293.1	—	—		
69			24.6	316.1	—	—		
('Electrolytic')				IVa(i)	p.c.			
27				—	0.195	211.0	1 313–1 673	39
51				—	249	312.3		
84			0.376	268.8	146	342.9		
()	()			IVb	p.c.			
			Diffusion of Ni^{63}					
202	—		0.356	274.6		fcc	95	
5.73			0.282	278.1		fcc		
9.47			0.12	265.4	fcc			
14.1			0.016	237.4		bcc		
20.1			0.007	224.4		bcc		
Cr	Fe	Ni						
()	()	()		IVa(i)	p.c.			
19.9	[a]	24.7	0.19	346.2	1.74	284.3	1 113–1 563	102
			(Ni)	IVb	p.c.			
			4.06	282.6	—	—	1 113–1 568	
()	()	()		IV Cr^{51}, Fe^{59}, Ni^{63}		p.c.		
17		12	0.13	264.2	0.37	279.7	873–1 573	135
					$A_{Ni} = 8.8$	$Q_{Ni} = 251.2$		
()	()	()		IVa(i)	p.c.			
17		12	6.3×10^{-2}	243.3	—	—	1 023–1 473	136
()	()	()		IVb	p.c.			
19	—	10	1.4	301.4	2.5×10^{-3}	217.7	1 173–1 473	137
		30	1.4	301.4	1.0	278.4		
	(wt.%)	45	2×10^{-4}	401.9	1.2	255.4		
		55	2.8	297.3	4.5	255.4		
		65	2.6	297.3	1.0	272.1		
		75	7.2×10^{-2}	253.3	4.10^2	343.3		
			Diff. of Ni					
(99.99)	(99.44)	(99.95)		IVb, p.c., Cr^{51}, Fe^{55}				
10.1	—	78.7	2.26	278.2	1.73	281.3		
10.1	—	64.6	1.35	273.4	1.10	276.5		
9.9	—	55.1	5.22	290.1	4.91	295.2		
10.1	—	35.0	8.49	299.1	3.75	295.1	1 286–1 536 (Fe)	162
20.0	—	63.5	2.18	282.3	2.22	286.7		
19.9 wt.%	—	55.1	4.72	295.8	7.62	307.8		
19.6	—	43.0	4.69	293.2	1.19	284.1	1 298–1 548 (Cr)	
20.0	—	34.9	1.95	282.8	4.75	298.7		
19.1	—	19.1	0.425	269.8	0.545	278.4		
30.4	—	65.3	1.945	279.3	1.23	280.1		
30.4		54.8	0.536	264.3	0.817	273.0		
30.4	—	34.8	5.82	294.5	2.42	291.0		
(5N)	(5N)	()	Diff. of S		IVb, p.c., S^{35}			
15	10 wt.%	—	0.46	213.6	—	—	1 173–1 473	166
()	()	()			IVa(i), p.c., Cr^{51}			
(19)	— [a]	10.4	5.59	296.5	—	—	1 216–1 311	171
()	()	()		IVa(i), p.c., Cr^{51}, Fe^{31}, Fe^{59}, Ni^{57}			Diff. of Ni	
15	—	20	8.3	309	5.3	308	1.5 300	177
15	—	45	4.0	293	2.1	288	1.8 293	
22	—	45	4.1	295	1.5	286	1.1 291	
15	—	20[b]	7.1	303	5.1	303	4.8 310	
				1 233–1 673 K				
()	()	()		IVa(i), p.c., Fe^{59}				
17	—	ii[c]	—	—	1.18×10^{-2}	228.5	1 178–1 483	78

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%		$A_1^{\dagger}$ $cm^2 s^{-1}$	$Q_1^{\dagger}$ $kJ\,mol^{-1}$	$A_2^{\dagger}$ $cm^2 s^{-1}$	$Q_2^{\dagger}$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
()	()	(99.8)		IVb p.c.	Diffusion of C^{14}			
0.74	0.52	—	—	—	0.1	142.4	873–1 173	36
4.65	0.36	—	—	—	0.5	154.9	773–1 173	
18	—	8			6.18	186.8	723–1 473	

(*a*) Plus 0.55 Nb, 0.74 Mn, 0.69 Si, 0.03 Ti.
(*a*) +1.33% Mn, 0.65% Si, 0.46% Ti, 0.44% Cu. (321 St. Steel).
(*c*) +2.3% Mo.

Cr	Ni						
('Electrolytic')			IVb	p.c.			
4.9		—	—	0.15	253.3		
6.35		0.01	211.4	—	—		
9.93		—	—	0.039	238.6	1 223–1 523	122
11.69		0.037	229.0	—	—		
19.7		0.01	242.8	0.0063	220.2		
()	(99.95)		IVa(i)	p.c.			
0		1.1	272.6	1.9	284.7	1 373–1 543 (D^*_{Cr})	
10		1.4	278.4	3.3	293.4	1 313–1 548 (D^*_{Ni})	42
20		1.9	283.4	1.6	286.8	1 040–1 404 (Ni Self *D*)	
(99.99)	(99.95)	IVb, p.c., Cr^{51}, Fe^{59}		Diff. of Fe			
—	95.8	—	—	2.48	285.9		
—	87.1	—	—	4.63	296.5		
—	78.5	7.40	297.8	5.33	299.9		
wt.%	73.0	—	—	1.475	287.0	1 286–1 536	162
—	68.3	—	—	1.16	285.1		
—	64.4	—	—	1.50	287.3		
—	55.3	—	—	1.84	286.6		
()	()	IVb, p.c., Ni^{63}, Cr^{51}					
20	—	0.61	264	0.15	259	1 123–1 473	173
(99.9)	(99.9)	IVb, p.c., Cr^{51}, Ni^{63}					
0	—	8.51	292.1	3.44	290.0		
4.7	—	6.37	292.1	1.32	279.5		
14.3	—	5.66	293.6	2.31	289.3		
23.6	—	6.10	295.5	2.95	293.8	1 223–1 473	192
29.4	—	2.91	288.5	1.02	285.4		
34.4	—	2.42	288.0	1.35	289.5		
38.4	—	2.16	284.0	1.43	290.4		
47.7	—	2.64	284.2	1.74	288.9		
()	()		IVa(i)	p.c.	IVa(ii)		
35(wt.%)		0.2	245.3	4.10^{-3}	205.2	1 223–1 633	68
80(wt.%)		0.28	259.6	—	—	1 423–1 688	
Cr	Ti						
	(99.4)	p.c.	IVa(ii)				
10.0		0.02	168.3		—	1 198–1 453	44
18.0		0.09	186.3		—		
Cr	Zr						
(99.99)	(99.9)		IV	p.c.	Cr^{51}		
1.5	(wt.%)	0.19	191.3	—	—	1 233–1 373(β)	49
(99.95)	(nuclear)	IVa(i), p.c., Cr^{51}, Zr^{95}					
0	—	4.53×10^{-3}	137.84	6.80×10^{-4}	145	1 218–1 518	
2.05	—	—	—	5.16×10^{-3}	165.2	1 200 1 497	
3.49	—	—	—	2.05×10^{-2}	169	1 196–1 518	195
4.08	—	—	—	1.38×10^{-2}	169.2	1 218–1 516	
7.86	—	—	—	1.59×10^{-2}	173.4	1 227–1 516	

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS - *continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* kJ mol^{-1}	A_2^* $cm^2 s^{-1}$	Q_2^* kJ mol^{-1}	*Temp. range* K	*Ref.*
Cu	Fe						
(99.998 5)	()		IVa(i)	p.c. and s.c.			
	0.2	$D^*_{Cu}/D_{Cu\ Pure}=0.99$				1 296	
	1.38	$=0.98$				1 296	
	1.38	$=0.91$				1 293	
	1.44	$=0.90$		$(b_1=-5\pm1.5)$		1 351	120
	1.45	$=0.94$				1 293	
	1.82	$=0.91$				1 265	
	2.40	$=0.90$				1 293	
Cu	In						
(99.998)	(5N)		IVa(i), p.c., In^{114m}				
—	0	—	—		$10^{10}D^*_{In}=7.0$		
—	0.8	—	—		$=9.8$		
—	1.7	—	—		$=13$	1089	179
—	3.1	—	—		$=18$		
—	5.1	—	—		$=34$		
(4NB)	(5N)		IVa(i), p.c., Cu^{64}				
—	0	0.6	210	—	—		
—	0.4	2.0	220	—	—		
—	0.8	0.4	200	—	—	1005–1 145	
—	1.2	0.6	200	—	—		
—	1.7	0.2	190	—	—		191
		$b_1=42$	$b_2=3\,500$			1005	
		$=43$	$=2\,300$			1089	
		$=48$	$=790$			1145	
Cu	Ni						
(99.99)	(99.95)	p.c.	IVa(i)				
0		0.57	258.3	1.9	284.7	1 323–1 633	
13.0		1.5	263.8	35.0	313.6	1 323–1 633	
45.4		2.3	252.5	17.0	279.7	1 258–1 483	32
78.5		1.9	231.5	0.063	208.1	1 133–1 343	
100.0		0.33	201.8	1.7	231.5	0 000–0 000	
()	()		Resistance method.	p.c.			
—	0	—	—	1.95	236.5		
—	1.08	—	—	0.95	233.1	1 053–1 310	182
—	2.81	—	—	0.23	225.5		
Cu	Ni Zn						
()	() ()		IVa(i)	p.c.			
100	— —	—	—	0.24	188.8	1 073–1 313	
89.9	— 10.1	—	—	0.64	190.9	1 022–1 252	
79.5	— 20.5	—	—	0.35	176.7	1 021–1 213	
69.8	— 30.2	—	— Diffusion	0.32	164.5	973–1 175	
90.7	9.3 —	—	— of Zn^{65}	0.36	200.1	1 068–1 313	90
80.4	— 10.3	—	—	0.49	195	1 023–1 278	
70.2	9.3 20.5	—	—	1.41	196.4	1 623–1 248	
60.1	9.1 30.8	—	—	0.39	173.3	973–1 173	
81.8	18.2 —	—	—	0.89	214.8	1 068–1 278	
70.8	18.8 10.4	—	—	0.36	199.7	1 073–1 313	
60.6	18.6 20.8	—	— Diffusion	0.73	187.1	1 021–1 213	
71.4	28.6 –	—	— of Zn^{65}	1.37	226.5	1 143–1 353	90
61.2	28.2 10.6	—	—	1.44	220.2	1 128–1 313	
50.8	28.2 21.0	—	—	1.17	208.9	800–1 005	
40.7	27.9 31.4	—	—	1.13	198.5	1 033–1 249	
Cu	Sb						
()	()		IVc	p.c.			
		D^*_{Cu}		D^*_{Sb}			
(δ)	19.4	4.10^{-10}		3.10^{-11}			
(χ)	24.4	7×10^{-9}		3.1×10^{-10}		663	61
(γ)	33.4	$\sim10^{-9}$		2.7×10^{-9}			

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
()	()		IVb	p.c.			
	21	8.57×10^{-3}	43.8	—	—		
(β)	25	1.99×10^{-3}	30.4	—	—	793–903	91
	29	5.80×10^{-3}	24.3	—	—		
(4N8)	(5N)	IVa(i), p.c., Cu^{64}					
—	0	0.6	210	—	—		
—	0.3	0.4	200	—	—	1 005–1 145	
—	0.5	0.6	200	—	—		
—	0.8	0.7	200	—	—		191
		$b_1 = 79$	$b_2 = 27\,000$			1 005	
		$= 100$	$= 14\,000$			1 089	
		$= 130$	$= 12\,000$			1 145	
Cu	Sn						
(99.999)	(99.999)		IVa(i)	p.c.			
(δ)	20.5	4.7	129.4	2.4×10^3	208.1	713–848	
(γ)	18.0	1.4×10^{-2}	74.5	0.33	122.3	873–998	92
	19.8	3.6×10^{-3}	84.6	9.2×10^{-2}	113.5		
(99.998)	(5N)	IVa(i), p.c., Sn^{113}					
—	0	—	—		$10^{10} D_{Sn}^* = 8.1$		
—	0.8	—	—		$= 9.6$		
—	1.7	—	—		$= 12$	1 089	179
—	3.0	—	—		$= 20$		
—	4.9	—	—		$= 26$		
(4N8)	(6N)		IVa(i), p.c., Cu^{64}				
—	0	0.6	210	—	—		
—	0.4	0.4	200	—	—		
—	0.8	0.07	180	—	—	1 005–1 145	
—	1.1	0.06	180	—	—		191
—	1.7	0.03	170	—	—		
		$b_1 = 40$	$b_2 = 9\,600$			1 014	
		$= 48$	$= 3\,300$			1 089	
		$= 54$	$= 2\,600$			1 145	
(5N)	(5N)		IVa(i), p.c., Cu^{64}, Sn^{113}				
—	16.6	8.3×10^{-3}	83	0.22	118	811–998	196
—	20.2	1.8×10^{-2}	82	3.5×10^{-2}	107	897–1 003	
Cu	Zn						
('Spec. P')	('Spec. P')	s.c.	IVa(i)				
(α)	31	0.34	175.4	0.73	170.4	850–1 178	45
	(99.99)	s.c.	IVa(i)				
		0.011	92.3	0.0035	78.6	Disord. 770–1 090	
		180	155.3	78.10^3	185.2	Ord. 653–723	
(β')	45.65 to 48.1	80	150.8	163.0	152.0	Ord. 537–653	46
		Diffusion of Sb					
		0.08	98.4			Disord. 771–867	
(—)	(—)			p.c.	IVa(i)		
		0.020	98.1	0.022	92.3	Disord. 773–1 073	
(β')	46.7	0.08	129.8[b]	1.0	134.0	Ord. around 573	47
(—)	(—)	p.c.	IVa(i)				
		Diffusion of Ag		Diffusion of Co			
(β')	47.2	0.014	91.7	0.47	112.6	Disord. 743–973	48

(*a*) Arrhenius plots in the ordered region are curved. The values of A and Q reported described straight line approximations to the data over the temperature ranges indicated.
(*b*) Ditto. The values of A and Q given here refer to the data at the lower end of the ordered temperature range investigated, viz: 300 K.
(*c*) Values of D^* for the ordered region are shown only in graphical form in reference 48.

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
()	()		IVa(i)	p.c.			
		$10^{10} \times D^*_{Cu}$		$10^{10} \times D^*_{Zn}$			
—	0	2.71		9.66		1 167	
		6.70		22.7		1 220	
—	0.62	2.81		—		1 167	
—	1.09	7.42		—		1 220	
—	2.17	3.12		—		1 167	93
—	2.68	3.23		—		1 167	
—	2.99	8.33		—		1 220	
—	4.06	3.71		—		1 167	
—	4.13	9.23		—		1 220	
(Electrolytic)	(99.99)		IVb	s.c.			
0		—	—	$\perp c$ 1.62	108.9	(d)	
0		—	—	$\parallel c$ 0.013	79.5		
0.2		—	—	$\perp c$ 3.2	108.9		
0.2		—	—	$\parallel c$0.021	79.3		
0.3		—	—	$\perp c$ 3.4	108.9	823–903	56
0.3		—	—	$\parallel c$ 0.025	79.5		
0.4		—	—	$\perp c$ 3.4	108.9		
0.4		—	—	$\parallel c$ 0.029	79.5		
0.5		—	—	$\perp c$ 3.5	108.9		
0.5		—	—	$\parallel c$ 0.035	83.7		

(*d*) Additions of 0.5 at % Al to this range of CuZn alloys have a negligible effect on Q_γ^{ne} but decrease $A_\perp$ by ~20% and A by ~40%.

Fe	Ge						
()	()		IVa	p.c.			
	4.8	4.8	242.8	—	—	1 173–1 473	75
Fe	Mn						
(99.97)	(99.94)		IVb	p.c.			
At.%	1.04	9×10^{-2}	265.4	5.5×10^{-2}	249.5		
	2.03	1.05×10^{-1}	262.9	2.0×10^{-2}	235.3		
	2.97	5.8×10^{-2}	255.8	9.6×10^{-3}	222.3		
	4.90	6.6×10^{-2}	255.0	1.7×10^{-2}	229.4	Fe	
	7.04	1.1×10^{-1}	262.1	7.2×10^{-2}	248.3	1 263–1 573	
	10.41	3.5×10^{-1}	275.5	2.9×10^{-1}	266.7	Mn	
	18.15	6.4×10^{-1}	282.2	1.9×10^{-1}	261.7	983–1 573	98
	25.5	8.5×10^{-1}	277.6	1.2×10^{-1}	251.6		
	33.98	6.0×10^{-1}	276.7	7.3×10^{-2}	242.0		
()	()		IVb	p.c.			
	wt.%	Diffusion of Ni^{63}					
	0.42	0.495	282.4				
	1.26	0.364	279.8			fcc range	95
	4.60	0.144	270.5				
	9.7	0.132	267.5				

Fe	Mn	Si					
(4N)	(4N)	()	IVa(i), p.c., $Nb^{94/95}$	Diff. of Nb			
—	1.5	0		0.66	264		
wt.%	1.5	0.6		1.4	271.7	1 354–1 474	184
—	0	0.6		1.29	270.0		

Fe	Mo						
()	()		IVb	p.c.	Fe^{59}		
	0.54	15.5	263.3	—	—		
(wt.%)	1.06	23.6	257.1	—	—	953–1 173	141
	1.50	23.6	257.1	—	—	Paramag.	
	2.50	47.7	264.2	—	—		

Fe	Nb					
()	()	IVa(i), p.c., Nb^{95}				
0–1.24	—	—	—	b_1 468.24	2029	
0–0.90	—	—	—	=56.8	2172	201
0–0.53	—	—	—	=55.0	2261	

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A^{\dagger}$ $cm^2 s^{-1}$	$Q^{\dagger}$ kJ mol^{-1}	$A^{\ddagger}$ $cm^2 s^{-1}$	$Q^{\ddagger}$ kJ mol^{-1}	*Temp. range* K	*Ref.*
Fe	Ni						
()	()		IVb	p.c.			
	0.2	—	—	1.09	290.3		
	0.55	—	—	1.09	290.3		
wt.%	2.29	—	—	0.593	281.8	sol. sol. range	95
	9.21	—	—	0.497	278.0		
	19.34	—		0.409	273.9		
(Electrol.)	(Electrol.)		IVc	p.c.			
	5.8	—		2.11	307.7	1 433–1 663	50
	14.88	—	—	5.0	316.5		
()	()		IVb	p.c.			
	20	18	314.0	—	—	1 073–1 573	29
	25	71	330.8	—	—	1 323–1 603	
()	()		IVa(i)	p.c.			
	50	—		66	322.8	1 286–1 508	96
	80	—	—	4.8	286.4		
()	()		IVa(i)	s.c.			
0 to 1.46	—	—	—	D^{*}_{Fe} nearly independent of composition		1 226 and 1 326	97
(99.44)	(99.95)	IVb, p.c., Fe^{59}, Cr^{51}					
—	0	0.88	279.7	Diff. of Cr			
—	15.5	1.96	286.5	1.96	280.5		
	30.7	5.35	298.9				
—	46.6	4.73	295.4	2.14	281.2		
wt.%	61.7	16.6	306.0			1 298–1 548	162
—	71.1	14.1	304.1				
	76.2	8.61	299.1	5.0	287.4		
	80.6	11.48	302.9				
—	90.5	12.88	303.4				
—	100	5.83	293.3				
(99.99)	(99.9)	IVb, p.c., Ni^{63}					
—	0	—	—	5×10^{-3}	232.4		
	5	—	—	1.5×10^{-2}	241.2		
wt.%	10	—	—	1.9×10^{-2}	243.2	1 193–1 513	172
—	15		—	0.277	270.5		
—	20	—	—	0.797	281.8		
(99.57)	(99.97)	IVa(i), p.c., Fe^{59}, Ni^{63}, W^{185}				Diff of W	
—	0	0.72	278.7	1.12	283.5	— —	
—	14.9	2.13	286.3	1.88	289.4	1.10 286.4	
	29.7	9.98	305.7	2.36	291.9	17.70 324.1	
—	45.3	8.75	301.8	8.04	303.4	13.90 320.5	
—	60.5	28.77	311.3	7.76	300.5	23.82 324.3	193
—	70.0	11.99	302.7	13.90	305.3	14.39 320.2	
—	75.3	20.28	309.9	13.31	307.3	10.69 317.0	
—	79.8	12.30	304.2	8.73	301.5	9.75 317.5	
—	90.0	17.99	307.1	7.67	299.6	2.06	299.5
—	100	9.21	297.7	3.44	290.0	— —	
				1 258–1 578 K			
Fe	Pd						
(99.97)	(99.95)		IVa(i)	Fe^{59} IVb Pd^{113}	p.c.		
0		0.18	260.0	0.04	249.5		
10		0.91	275.9	0.37	268.4		
20		0.91	269.6	0.79	271.3		
30	(At.%)	0.60	259.6	0.73	266.7		
40		0.69	258.7	0.79	266.3		
45		0.79	260.0	0.67	263.8	1 373–1 523	142
50		0.95	262.5	0.70	264.6		
60		0.95	264.2	1.05	270.9		
70		0.66	262.5	1.66	279.3		
80		0.93	271.7	1.84	284.7		
90		0.79	277.6	0.70	278.8		
100		0.41	280.9	0.41	280.9		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A_1^{\uparrow}$ $cm^2 s^{-1}$	$Q_1^{\uparrow}$ $kJ\,mol^{-1}$	$A_2^{\updownarrow}$ $cm^2 s^{-1}$	$Q_2^{\updownarrow}$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Fe	Pt						
()	()		IVb p.c. Pt^{193m}				
	0	—	—	2.7	296.0		
	15	—	—	1.1	264.2		
	20	—	—	0.34	265.0		
	25	—	—	1.17	265.0		
	30	—	—	0.28	264.2		
	34	—	—	0.15	264.2	1 053–1 693	138
	40	—	—	1.3	289.7		
	45	—	—	1.13	284.3		
	50	—	—	2.1	292.2		
	55	—	—	0.85	286.8		
	60	—	—	0.34	280.9		
Fe	Sb						
()	()		IVa	p.c.			
	2.5	0.51	216.9			1 169–1 370	75
Fe	Si						
(99.999)	(99.99)		IVa and b	p.c.			
	0	1.39	236.6	—	—		
	4.7	1.63	232.4	—	—		
	6.3	0.50	229.9	—	—	1 073–1 573	100
	8.2	0.50	213.1	—	—		
	11.3	1.11	213.9	—	—		
	11.7	1.46	216.5	—	—		
()	()		IVb	p.c.			
	2.9	0.44	218.5	—	—	1 240–1 689	123
()	()		IVa(i) s.c.	Fe^{59}			
	7.64	1.38	228.2	—	—	1 173–1 373	139
(At.%)	11.1	0.63	212.3	—	—		
()	()	IVa(i), p.c., Fe^{59}					
—	0	2.73	242	—	—		
—	1.48	1.03	276	—	—		
—	1.87	76.7	276	—	—	1 073–1 373	188
—	6.55	5.2	242	—	—		
—	8.64	4.93	236	—	—		
—	12.1	0.8	213	—	—		
(99.95)	()			IVb, Fe^{59}, s.c.			
—	5.5	7.2	250	—	—		
—	6.4	3.15	238	—	—		
—	7.8	8.6	244	—	—	1 013–1 373	203
—	11.6	0.63	212	—	—		
—	15.3	2.1	219	—	—		
—	192	3.4	216	—	—		
(4N)	(4N)	IVb, p.c., Fe^{59}					
—	10	5.59	219.1	—	—	875–957(α–f)	197
—		0.25	209.6	—	—	1 005–1 178 (α–p)	
Fe	Sn						
(99.97)	(5N)	IVa(i), p.c., Fe^{59}					
—	0–26	$b_1 = 98$		—	—	1 168	
		$= 63$		—	—	1 093	159
		$= 63$		—	—	1 009	
Fe	Ti						
()	()		IVa	p.c.			
	2	2.8	242.0	—	—	1 173–1 473	75
()	()		IVa(i)	p.c.			
	2	0.56	216.5	—	—		
	4	0.27	204.7	—	—	1 273–1 673	99
	6	0.40	209.9	—	—		
()	()		IVa(i)	p.c.			
	33.32	11.7	314.0	—	—	1 123–1 373	125
(a)	50.0	0.135	239.5	—	—		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
(Spec. P.)	(99.7)	IVa(ii)	p.c.	Diffusion of Nb^{95}			
5		9.2×10^{-2}	165.8	1.82×10^{-3}	196.1	1 123–1 533	53
10		2.14	203.5	2.9×10^{-2}	172.9	1 123–1 473	
15		52.5	243.3	9.9	234.5	1 123–1 373	
Fe	V						
(—)	(—)		IVb	p.c.			
(γ)	0.53	1.46	288.5	—	—	1 373–1 573	54
(γ)	1.09	0.53	277.2	—	—		
(α)	2.11	0.10	257.5	—	—		
(—)	(—)		IVa(i)	p.c.		(Paramag.)	
	18.0	7.0	258.3	3.9	244.9	1 153–1 473	55
(99.98)	(—)		IVb	p.c.			
		Diffusion of Hf^{181}					
—	2.1	1.31	290.1	3.92	241.2	1 273–1 673	94
(99.999)	()		IVa	p.c.			
—	1.8	1.4	237.0	—	—	1 173–1 773	75
—	5.3	1.87	240.3	—	—	1 173–1 466	
()	()		IVb	p.c.			
	2	—	—	3.92	241.2	1 273–1 723	99
	5	—	—	3.00	238.6		
	9	—	—	2.28	236.1		
	14	—	—	2.12	236.6		
	19	—	—	1.66	234.0		
()	()	Diffusion of Cr^{51}					
	1.7	2.0	238.6	—	—	—	88
()	()	IVb, p.c., V^{48}					
—	0	—	—	2.04	229.8	1 233–1 511	183
—	5.4	—	—	2.10	231	1 255–1 511	
—	10.9	—	—	2.2	234	1 255–1 511	
—	16.25	—	—	2.02	235	1 233–1 466	
wt.%	20.0	—	—	10	255	1 233–1 466	
—	27.65	—	—	1.8	238	1 255–1 511	
—	47	—	—	45	293	1 503–1 593	
—	65	—	—	530	346	1 233–1 466	
—	75	—	—	3.47×10^4	403	1 233–1 466	
—	90	—	—	164	355	1 233–1 466	
()	()	IVa, p.c., V^{48}					
0–1.11	—	—	—	$b_1 = 18.7$		1 573	169
0–0.96	—	—	—	$= 10.0$		1 757	
0–1.11	—	—	—	$= 12.6$–15.6		2001	
(Marz)	(Marz)	Diff. of C		IIa(ii), p.c., C^{14}			
—	2.45	54.7	170.4	—	—	1 173–1 598	185
Fe	Zr						
()	()	IVa(i), p.c., Fe^{59}, Zr^{95}					
0–3.5	—	—	—		$b_1 = 47$	1221	156
		$B_1 \sim 0$		—	—	1 078–1 578	
(99.9)	(nuclear)	IVa(i), p.c., Fe^{59}, Zr^{95}					
0	—	4.47×10^{-3}	117.1	6.8×10^{-4}	145	1 218–1 518	195
0.98	—	—	—	1.52×10^{-3}	149.04	1 258–1 518	
1.35	—	—	—	2.08×10^{-3}	150.9	1 218 × 1 518	
1.64	—	—	—	1.62×10^{-3}	145.97	1 196–1 520	
3.54	—	—	—	2.9×10^{-3}	140.8	1 188–1 470	
6.37	—	—	—	5.26×10^{-2}	155.45	1 276–1 513	
Ga	Pu						
()	()		IVa(i)	p.c.			
1.0(wt)	—	—	—	76.4	152.0	613–781(δ)	114
		—	—	6.98×10^{-4}	56.1	847–917(ε)	

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Ga	V						
(6N)	(99.9)		IVa(i), p.c., V^{48}				
25	75 V_3(Ga)	—	—	1.52×10^4	414.8	1 298–1 449	160
Ge	Ni						
(3N6)	(3N6)	IVa(iii), p.c., Co^{59}					
0–8	—	—	—	$b_1 = 6$	$b_2 = 421$	1 333	
				$= 10$	$= 264$	1 380	51
				$= 3$	$= 221$	1 418	
				$= 2$	$= 137$	1 471	

Enhancement not of D^*_{Si} but of the closely similar (*sic*) D^*_{Co}.

In	Pb						
()	()	IVa(i), p.c., Pb^{210}					
7	—	—	—	7.2×10^{-4}	69.1	468–558	187
12	—	—	—	5.1×10^{-4}	64.0		
0–30	—		$b_1 = 64.5$	$b_2 = 285.3$		516	
()	()	IVa(i), p.c., Ag^{110m}		Diff of Ag			
0	—	—	—	4.6×10^{-2}	60.3		
2	—	—	—	2.4×10^{-2}	56.9		
7	—	—	—	3.5×10^{-2}	54.8		
12	—	—	—	3.66×10^{-2}	52.4	403–523	145
20	—	—	—	1.33×10^{-2}	45.0		
30	—	—	—	6.5×10^{-3}	39.3		
45	—	—	—	4.4×10^{-3}	36.8		
In	Pd						
(6N)	(4N)	IVa(i), pc., Pd^{109}, In^{114m}					
51	49	84.10^{-3}	192	0.12	207	1 056–1 270	
		$+5 \times 10^2$	314.5				
50	50	5.0×10^{-3}	181	2.30	243	996–1 327	
		$+1.06 \times 10^3$	318				161
47	53	1.6×10^{-2}	191	0.60	222	996–1 425	
		+20.0	293				
44	56	0.14	215	0.20	205.5	1 039–1 473	
K	Na						
(99.97)	(99.999 5)		IVa(i)	p.c.			
		—	—	$D^*_{Na} \times 10^9$			
0				1.34			
0.13				1.38			
0.14				1.44			
0.19				1.54			
0.33				1.58		273	
0.49				1.81			
0.56				1.79			
0.67				1.90			
1.03				2.12			
				$D^*_{Na} \times 10^8$			108
0				2.16			
0.13				2.28			
0.18				2.26			
0.38				2.39		373	
0.55				2.61			
0.73				2.86			
1.25				3.40			
Mn	Pt						
()	()		IVa(i), p.c., Mo^{54}				
18	—	2.1×10^{-10}	53	—	—	1 020–1 284	
25	— ($MnPt_3$)	3.0×10^{-2}	222	—	—	1 026–1 283	181
35	—	2.3×10^{-10}	57	—	—	1 026–1 284	

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A^{\uparrow}$ $cm^2 s^{-1}$	$Q^{\uparrow}$ $kJ\,mol^{-1}$	$A^{\updownarrow}$ $cm^2 s^{-1}$	$Q^{\updownarrow}$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Mn	Ti						
(99.97)	(99.97)		IVa(i)	p.c.			
9.7		—	—	1.9×10^{-2}	171.2	1 133–1 723	121
13.3		—	—	2.06×10^{-2}	172.1	1 073–1 623	
17.9		—	—	2.60×10^{-2}	176.3	1 070–1 573	
20.6		—	—	5.47×10^{-1}	207.7	1 083–1 523	
Mn	Zr						
()	()	IVa(i)	p.c.	Mn^{54}	Zr^{95}		
0		5.38×10^{-3}	140.7	0.31×10^{-4}	105.3		
0.5		2.92×10^{-3}	135.7	0.71^{-4}	112.3		
1.0		1.38×10^{-3}	125.5	1.2×10^{-4}	116.7	1 173–1 473	143
1.5		4.6×10^{-4}	2.17×10^{-4}	121.8			
2.0		8.0×10^{-5}	104.6	3.36×10^{-4}	125.3		
Mo	Ni						
()	()		IVa	pc.c			
8		1.31	229.9	2.55	236.1	1 272–1 673	
16		1.3	228.6	0.63	218.6	1 273–1 623	
18		0.45	218.6	0.34	218.6	1 223–1 623	126
20		0.25	210.6	0.19	204.3	1 223–1.573	
23		0.20	207.2	0.12	198.5	1 373–1 573	
(99.4)	(99.4)	IVb	p.c.	Diffusion of C^{14}			
2.94		—	—	1.0	159.1	873–1 173	36
Mo	Ti						
(99.98)	(99.62	IVb	p.c.	Diffusion of U^{235}			
5				0.26	206.4		
10				1.45	237.4		
15				2.88	249.5	1 173–1 673	116
20				2.69	270.5		
25				6.03	288.9		
30				33.0	314.0		
Mo	U						
(—)	(—)		IIa(ii)	p.c.			
0		—	—	1.8×10^{-3}	115.1	1 073–1 313	57
10		—	—	2.5×10^{-3}	138.2		
Mo	W						
()	()		lVa	p.c.			
	0.1	142	468.9	0.007 5	297.3	2 073–2 673	104
	15	265	448.8	1.4	305.6		
	20	146	427.1	1.7	312.3	1 673–2 673	
	25	47	397.7	2.2	322.4		
	35	28	385.2	6.9	355.9	1 773–2 673	
	50	12	368.4	14	397.7	1 973–2 773	
	65	1.3	360.1	16	427.1	2 073–2 873	
	75	0.2	353.8	20	485.7		
	80	0.11	342.3	22	498.2	2 073–3 073	
	85	0.08	334.9	25	570.8		
	99.9	0.002 5	326.6	24	544.3	2 473–3 073	
()	()		IVa	p.c.			
44	—	0.17	448.0	—	—	2 173–2 673	105
55	—	0.12	431.2	—	—		
Nb	Ni						
()	()		IVb s.c.	Ni^{63}	Nb^{95}		
25	75	2.4×10^2	448.0	—	—	1 543–1 623	144
		—	—	0.18	304.8	1 363–1 643	
(99.9)	(99.99)		IVa(i)	p.c.			
1.2		—	—	0.12	254.6		
8		—	—	0.20	260.4	1 303–1 503	113
10		—	—	1.80	280.9		

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity*) At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Nb	Ti						
(99.6)	(99.7)	p.c.	IVa(ii)	Diffusion of Fe^{55}			
5		1.2×10^{-4}	125.2	7.9×10^{-3}	138.6		
10		5.8×10^{-4}	151·1	115×10^{-3}	146.1	1 123–1 573	53
15		1.5×10^{-3}	164.5	7.9×10^{-3}	146.5		
31		9×10^{-3}	209.3	—	—	1 323–2 073	
54		8×10^{-2}	268.0	—[a]	—	1 473–2 073	58
66		0.1	301.4	—	—	1 773–2 273	
89		1.0	381.0	—	—	1 973–2 473	
Nb	Ti						
()	(99.97)		IVa(i) p.c.	Ti^{44}	Nb^{95}		
	100	2.9×10^{-4}	129.9	4.54×10^{-4}	131.0		
(At.%)	94.6	1.79×10^{-3}	160.0	1.27×10^{-3}	149.1	1 223–1 784	147
	80.4	1.18×10^{-2}	198.2	3.15×10^{-3}	175.7		
	64.3	2.98×10^{-1}	258.5	2.51×10^{-1}	247.1		
()	()	IVb	p.c.	Diffusion of U^{235}			
5				0.022	170.4		
10				0.035	182.1		
15				0.11	201.0		
20				0.26	215.6	1 173–1 673	116
25				0.25	226.1		
30				0.42	235.7		
Nb	U						
()	()		IVb	p.c.			
0		1.2×10^{-5}	119.3	1.1×10^{-4}	150.7		
5				3.2×10^{-6}	142.4	1 223–1 323	
10				3.5×10^{-6}	147.4		
20				10^{-5}	165.8		
35		3.1×10^{-2}	288.1	1.25×10^{-4}	222.7	1 323–1 493	
50		3.1×10^{-2}	304.4	2.5×10^{-4}	239.5	1 475–1 123	153
65		7.6×10^{-2}	324.5	4.0×10^{-3}	274.7	1 473–1 773	
80		1.1	383.1	6.3×10^{-4}	280.5	1 823–2 073	
90		5.2	421.2	2.5×10^{-3}	305.6	1 973–2 173	
100		0.91	421.2	6.5×10^{-6}	321.1	2 073–2 273	
()	()		IIa(ii)	p.c.			
10	—	—	—	1.66×10^{-4}	118.1	1 073–1 313	57
Nb	W						
()	()	IVa(i), p.c., Nb^{95}, W^{185}, Zr^{95}					
—	0	$D^*_{Nb}=1.434\times10^{-8}$		$D^*_W=4.58\times10^{-9}$			
—	2	$=1.277\times10^{-8}$		$=4.35\times10^{-9}$			
—	5	$=1.065\times10^{-8}$		$=3.30\times10^{-9}$			
—	10	$=7.60\times10^{-9}$		$=2.38\times10^{-9}$			
		$b_1=-5.7$		$B_1=-5.7$		2 680	153
		Diff. of Zr					
—	0	$D=4.42\times10^{-8}$					
—	2	$=3.86\times10^{-8}$					
—	5	$B_i^{Zr}=-5.7$ $=3.28\times10^{-8}$					
—	10	$=2.42\times10^{-8}$					
Nb	Zr						
(99.99)	(99.9)		IV p.c.	Nb^{95}			
2.3	wt.%	1.63×10^{-3}	162.4	—	—	1 173–1 433	49
()	()	IVa(i), p.c., Zr^{95}. $D^*_{Zr}=A_2\exp(-Q_2/kT)\exp(B/kT^2)$					
				A_2	Q_2	B	
5.5	–	–	–	0.44	315	1.34×10^5	
16.3	–	–	–	0.43	285	8.30×10^4	194
28.1	–	–	–	0.13	261	5.50×10^4	
()	()	Diff. of Ni		IVa(i), p.c. Ni^{63}			
2.5 wt.%	—	$D=8.9\times10^{-12}$				1 120.8	155
		$D=1.1\times10^{-13}$				893.6	

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	$A_1^\dagger$ $cm^2 s^{-1}$	$Q_1^\dagger$ $kJ\,mol^{-1}$	$A_2^\ddagger$ $cm^2 s^{-1}$	$Q_2^\ddagger$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
()	()	Diff. of Co		IVa(i), p.c., Co^{57}			
32	—	8.7×10^{-2}	154			1 125–1 645	156
Nb	Zr Mo		IVb	p.c.			
()	() ()						
5	95 —	4.6×10^{-2}	209.5	4.1×10^{-3}	169.6		
10	90 —	4.4×10^{-1}	230.3	2.8×10^{-2}	196.8		
15	85 —	5.5×10^{-1}	242.8	8.6×10^{-2}	211.4		
2.5	— 2.5	7.6×10^{-2}	213.5	9.0×10^{-3}	180.0		
5	— 5	3.1×10^{-1}	234.5	5.4×10^{-2}	207.2	1 473–1 773	119
7.5	— 7.5	1.1	251.2	2.8×10^{-1}	230.3		
—	95 5	—	—	6.4×10^{-3}	175.8		
—	90 10	—	—	6.6×10^{-2}	205.2		
—	85 15	—	—	2.10^{-1}	224.0		

(*a*) Values read from graphically plotted results.

Nb	Zr O		IV	p.c.	O^{18}		
()	() ()						
	0.5	—	—	1.83×10^{-3}	110.1	873–1 373	
wt.%	0.8	—	—	1.07×10^{-3}	108.4	873 × 1 373	146
	1.0	—	—	4.11×10^{-4}	103.4	873–1 373	
				(O Diffusion)			
Ni	Pb						
()	(6N)	IVb, s.c., Ni^{63}					
sat. sol.		$B_1 = 77\,000$		Fitted to		408	
soln		$= 50\,000$		$D^*_{Ni} = 2A(c=0)/[1+(1-4B_1c)^{1/2}]$		416	202
		$= 15\,000$				450	
		$= 7\,000$				515	
Ni	Sb						
()	()		IVb	p.c.			
71.7		5.4×10^{-4}	61.5	—	—		
72.9(β)		4.9×10^{-4}	62.0	—	—	873–1 272	101
73.7		6.3×10^{-4}	66.2	—	—		
75.0		6.9×10^{-4}	69.1	—	—		
()	()		IVa(i), s.c. and p.c., Ni^{63}, Sb^{124}				
50(γ)	50 p.c.	0.019	161	1.84	278	860–1 373	
53(γ)	47 p.c.	0.051	159	0.58	258	(Ni)	154
53(γ)	47 s.c.	$\perp c$ 0.095	163	3.4	281	1 150–1 373	
		$\parallel c$ 0.082	165	7.3	284	(Sb)	
Ni	Si						
(3N6)	(3N6)		IVa(iii), p.c., Co^{59}				
—	0–8	$b_1 = 3$	$b_2 = 156$			1 410	51
—	—	$= 2$	$= 174$			1 465	

Enhancement not of D^*_{Ni} but of the closely similar (*sic*) D^*_{Co}.

Ni	Sn				
(99.98)	(5N)	IVb, p.c., Ni^{63}, Sn^{113}			
—	0–2.0	$b_1 = 55$	$b_2 = 770$	1 373	163
—	0–4.0	$D^*_{Sn} = 3.1\times10^{-10}\exp 0.191\,N_{Sn}(at.\%)$			
(3N6)	(3N6)	IVa(iii), p.c., Co^{59}			
—	0–90	$b_1 = 3$	$b_2 = 276$	1 419	51
—	0–7.3	$= 3$	$= 225$	1 472	

Enhancement not of D^*_{Ni} but of the closely similar (*sic*) D^*_{Co}.

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity* At.%	A_1^* $cm^2 s^{-1}$	Q_1^* $kJ\,mol^{-1}$	A_2^* $cm^2 s^{-1}$	Q_2^* $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*	
Ni	Ti							
()	()		IVa(i)	p.c.				
	2.44	2.24	287.2	—	—	1 202–1 501	124	
	4.86	1.51	282.6	—	—			
	7.24	0.91	277.2	—	—			
	9.63	6.6	296.0	—	—			
	12.68	3.0	319.0	—	—			
	25	6.9×10^{-3}	389.0	—	—			
Ni	W							
(99.95)			IVa(i)	p.c.				
	0	1.9	284.7	2.0	299.4	1 369–1.668 (D_{Ni})	66	
	1.7	30.0	320.3	2.2	306.1			
	5.3	58.0	337.5	17.0	337.0.	1 373–1 568 (D_W)		
	9.2	1.1	294.3	1.4	311.9			
Pb	Sn							
(5N)	(5N)	Diff. of Ag		IVa(i), p.c., Ag^{110m}				
—	0	4.6×10^{-2}	61			423–573	168	
—	5	4.8×10^{-2}	60					
—	8.4	2.0×10^{-2}	56					
—	12	2.2×10^{-2}	55					
Pb	Tl							
(99.99)	(99.99)		IVa(i)	p.c. (except 62.6%)				
100	0	1.372	109.1	0.511	101.9	479–596	59	
	5.21	1.108	107.8	0.364	100.0			
	10.27	0.880	106.6	0.361	99.8			
	20.2	0.647	104.9	0.353	99.6			
	34.6	0.367	102.7	0.193	96.8			
	50.3	0.231	102.3	0.091	94.3			
	62.4	0.393	107.3	0.101	96.0			
	62.6(s.c.)	0.287	105.9	0.126	97.1			
	74.5	0.691	112.3	0.194	99.9			
	76.2	0.862	113.6	0.330	102.5			
	81.8	2.575	118.2	0.957	106.2			
	87.1	17.0	124.4	1.20	106.9			
Pu	Zr							
()	()		IVb p.c.	Pu^{240}				
At.%	40	0.04	124.1	—	—	913–1 113	148	
	10		$D_1 = 1.05 \times 10^{-7}$	—	—	923		
Sc	Zr							
()	()	IVa(i), p.c., Zr^{95}		$D_{Zr}^* = A_2 \exp(-Q_2/kT) \exp(B/kT^2)$				
				A_2	Q_2	B		
6.7	—	—	—	1.0	336	1.63×10^5	1 300–1 906 / 1 416 × 1 873	194
13.5	—	—	—	1.3	343	1.72×10^5		
	(99.6)		IVb	p.c.				
0		—	—	5.9×10^{-2}			923–1 100	60
1.0		—	—	5.0	259.6		740–827	
1.85		—	—	2.1×10^{-3}	314.0			
2.75		—	—	10	268.0			
()	99.99)	Diff. of Cr		IVa(i), p.c., Cr^{51}				
0	—	7.4×10^{-3}	143			1 255–1 513	165	
0.45	—	4.5×10^{-3}	137.8					
1.75	—	2.5×10^{-3}	132.3					

Table 13.3 DIFFUSION IN HOMOGENEOUS ALLOYS—*continued*

Element 1 (*purity*) At.%	*Element 2* (*purity*) At.%	$A_1^\dagger$ $cm^2 s^{-1}$	$Q_1^\dagger$ $kJ\,mol^{-1}$	$A_2^\dagger$ $cm^2 s^{-1}$	$Q_2^\dagger$ $kJ\,mol^{-1}$	*Temp. range* K	*Ref.*
Ta	V						
()	()	IVa(i), p.c., V^{48}					
0–1.04	—	$b_1 - 1.68$		—	—	1960	169
(—)	(99.98)		IVa(i)	p.c.			
0							
10	–						
20	—						
30	—	Curved Arrhenius plots		Curved Arrhenius plots			
40	—	*See* Figure 13.8a		*See* Figure 13.8b		1173–2073	115
50	—	The lines of Figures 13.3a and 13.3b are drawn at					
60	-	10 at.% intervals of composition as shown in column 1					
70	—						
80	—						
90	—						
()	()	IVa(i), p.c., V^{48}		$D_2^\dagger = A_2 \exp(-Q_2/kT)\exp(B/kT^2)$			
				A_2 Q_2 B			
—	9.4	—	—	1.1 307 1.08×10^3			115 and
—	19	—	—	1.9 310 1.00×10^3			194
()	()	IVb	p.c.	Diffusion of U^{235}			
—	5			0.034	172.5		
—	15			0.063	182.1		
—	15			0.047	182.1		
—	20			0.0096	164.5		
—	25			0.025	177.9		116
—	30			0.089	195.5	1173–1673	
—	40			0.12	206.8		
—	50			0.65	235.7		
—	60			2.7	288.9		
—	70			5900	365.1		
U	Zr						
(—)	()		IIa(ii)	p.c.			
	10	1.26×10^{-4}	92.1	—	—	1073–1313	57
()	()		IIa(ii)	p.c.	IVa(i)		
	95	$D_U^* - 1.5 \times 10^{-9}$	—	$D_{Zr}^* = 3.2 \times 10^{-9}$	—	1273	62
		$D_U^* 1.85 \times 10^{-9}$	—	$D_{Zr}^* = 4.2 \times 10^{-9}$	—	1323	
()	()		IVa(i)	p.c.			
0	—	5.7×10^{-4}	127.7				
11	—	7.5×10^{-4}	141.9	0.12	205.6		
27	—	3.65×10^{-3}	160.8	2.8×10^{-2}	190.5		
39	—	7.10^{-3}	168.7	3.9×10^{-4}	146.5		
59	—	8.96	245.3	2.4×10^{-3}	118.5	1173–1338	117
78	—			3.8×10^{-6}	99.2		
85	—			7.5×10^{-7}	83.7		
100	—			1.6×10^{-7}	68.7		
V	Zr						
(99.95)	(nuclear)	IVa(i), p.c., V^{48}, Zr^{95}					
—	0	118	389.3	81	369.2		
—	0.5	86	383.2	115	373.0		
—	1.0	72	379.4	153	376.0	1578–1888	
—	1.5	68	376.7	195	378.6		
—	2.0	58	373.0	242	380.8		167
		1578 K 1633 K 1688 K 1738 K 1783 K 1848 K 1888 K					
		$b_1 -$ 28.7 26.5 24.4 19.9 15.0 16.9 17.7					
(99.95)	(nuclear)	IVa(i), p.c., V^{48}, Zr^{95}					
0	—	8.9×10^{-5}	116.55	3.1×10^{-5}	105.25		
0.5	—	5.5×10^{-5}	112.47	4.5×10^{-5}	109.02		
1.0	—	3.0×10^{-5}	106.88	5.9×10^{-5}	111.95	1166–1480	
1.5	—	1.5×10^{-5}	100.55	9.3×10^{-5}	116.83		
2.0	—	0.7×10^{-5}	94.15	14.0×10^{-5}	120.79		
		1167 K 1223 K 1281 K 1318 K 1375 K 1428 K 1476 K					
		$b_1 = -4.14$ 0 2.8 5.09 8.71 10.41 13.60					
()	()	IVa(i), p.c., V^{48}					
—	0.5	0.64	312.6	—	—	1428–2078	189

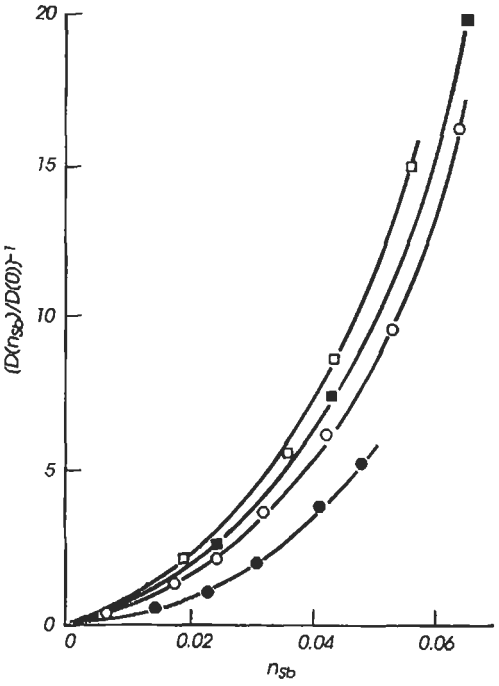


Figure 13.7

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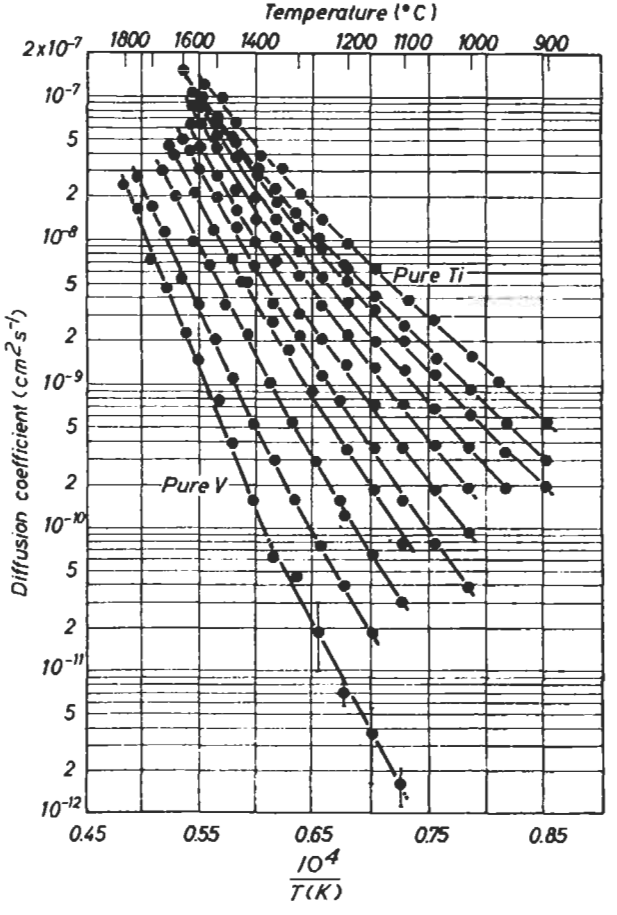


Figure 13.8a *Temperature dependence of diffusion of* Ti^{44} *in titanium–vanadium alloys*[115] *at* 10 at.% *intervals*

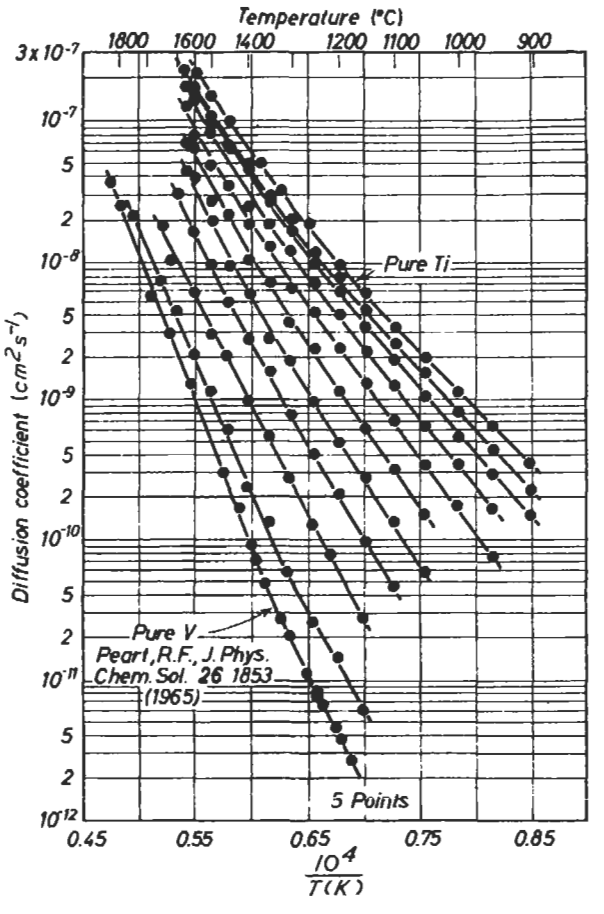


Figure 13.8b *Temperature dependence of diffusion of* V^{48} *in titanium–vanadium alloys*[115] *at* 10 at.% *intervals*

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Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
A	Ag						
V. small	~100	0.12	140.7	—	873–1 073	IIIb(ii)	1
A	Mg						
V. small	~100	10^4	218	—	603–813	IIIb(ii)	104
Ag	Al						
0.5		0.21	120.6				
1.0		0.30	123.5				
1.5		0.33	124.8	A few partial D_{Ag}'s			
2.0		0.55	128.95	and D_{Al}'s calculated.	773–868	IIa(i)	2
2.5		0.78	131.5	Very roughly			
3.0		1.50	136.1	$\tilde{D} = D_{Ag} \sim 2D_{Al}$			
3.5		3.0	141.1				
6.5		11.0	154.9				
8.5		16.0	159.1				
—	0–20	1.63	153	—	648–793		
		$\log \tilde{D} = -13.360 + 7.316c$			648	Electrochem. method	292
(c = mol fraction)		$\log \tilde{D} = -10.601 - 1.084c + 11.392c^2$			723		
		$\log \tilde{D} = -10.322 + 1.799c$			793		

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Ag	Au						
0–8.77		0.0242	154.9		1 079–1 290	IIa(ii)	3
45.0				4.7×10^{-9}			
54.0				4.1×10^{-9}			
64.0				3.7×10^{-9}	1 213	IIIa(i)	4
75.0				2.8×10^{-9}			
85.0				1.9×10^{-9}			
50.8		0.14	174.6		1 036–1 238	IIa(i)	5
Ag	Cd						
—	0–25		*See* Figures 13.9 and 13.10		873 1 073	IIa(i). p.c.	291
—	8.6		$D_{Cd}/D_{Ni} = 150$		1 073		
	16.5		1.54				
—	3.4	—	—	$11.2 \times 10 \times 10^{-9}$	1 179.5		
—	10.4	—	—	4.3×10^{-9}	1 072.4		
—	10.7	—	—	[a] 5.4×10^{-9}	1 087		
—	16.45	—	—	[a] 6.71×10^{-9}	1 073.5		
—	17.1	—	—	9.36×10^{-9}	1 073.5	IIa(i), s.c.	51
			$10^9 D_{Ag}$	$10^9 D_{Cd}$			
—	3.4		1.85	11.53	1 179.5		
—	10.8		1.67	5.76	1 086.6		
—	16.5		1.32	[a] 7.79	1 073.5		
—	17.1		2.77	10.72	1 073.5		

(*a*) Average values.

Ag	Cu						
0–3		0.012	149.1	—	990–1 140	IIa(ii)	6
	0–2	0.52	183.8	—	1 023–1 073	IIa(ii)	156
Ag	Ga						
	1.9–9.5	0.42	162.9	—	1 023–1 073	IIb	219
Ah	H						
	0–sol. limit	2.82×10^{-3} (D indep. of conc.)	31.4	—	611–873	IIb(ii)	7
Ag	Kr						
~100	V. small	1.05	146.5	—	773–1 073	IIIb(ii)	8
Ag	Mn						
—	0–8.5	0.18	179.6	D indep. of conv.	849–1 206	IIa	151
Ag	Ne						
~100	V. small	2.5	249.1	—	1 073–1 213	IIIb(ii)	105
Ag	O						
	0–sol. limit	3.66×10^{-3}	46.1	—	685–1 135	IIIb(ii)	9
Ag	Pb						
0–0.12		7.4×10^{-2}	63.6	—	493–558	IIa(ii)	10
Ag	Pd						
50	50	1.5×10^{-6}	103.0	—	873–1 173	II	152
Ag	S						
	Sol. soln	2.34×10^{-3}	110.1	—	877–1 025		220
Ag	Xe						
~100	V. small	0.036	157.0	—	773–1 073	IIIb(ii)	13
Ag	Zn						
(β)	50	0.0164	69.1	$D_{Zn} \sim 3$ to $4 D_{Ag}$	673–883	IIc / IIa(i)	11
	40–55			Figure 13.11			
(α)	26.8			8.7×10^{-9}	at 973	IIIa(i)	12
	27.6			2.45×10^{-9}	at 923		
				$D_{Zn} \sim 1.5$–$2.2 D_{Ag}$			
α-phase	0–18	*See* Figures 13.12 and 13.13		—	823–1 023	IIa(i), p.c.	312
(ε)	74–87	*See* Figure 13.19			583–673	IIa(i)	221

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Al	Au						
33.33	66.66	6.8	105.5		393–553	IIc, p.c.	263
'α-phase'		—	~138	2.6×10^{-13}	573	p.c., IIa(ii)	265
(*Au*Al)		—		1.1×10^{-10}	723		
Al	Be						
	0.015	52	163.3				
	0.022	126	168.7	—	773–908	IIa(iii) and IIc	14
	0.03	550	180.5				
Al	Co						
0–10.2		10.5	295		1 273–1 473	IIa(i), p.c.	257
Al	Cr						
—	0–6	1.3×10^6	240		659–726	IIa(i), p.c.	276
Al	Cu						
	0–0.215	0.29	130.29		778–908	IIa(ii)	15
	0–~2 (sol. sol. range)	0.18	126.02	—	775–811	IIc	154
0		0.131	185.22	—			
2		0.231	187.74				
4		0.287	187.57	—			
6		0.364	187.19 [a]	—	985–1 270	IIa(i)	153
8		0.588	189.37	—			
10		1.033	194.43				
12		1.293	191.46				
~25	(β)	0.19	115.1	—	919–1 023	IIc	17
	(γ_2)	0.85	136.1	—			
	(δ)	2.1	138.2				
	(ζ_2)	1.6×10^4	230.7	—	673–808	IIc	155
	(η_2)	2.2	148.6	—			
	(θ)	0.56	127.7				
11–13 wt.%	β-phase	0.65 $A_{Al} = 0.13$ $A_{Cu} 2.2$	176.7 $Q_{Al} = 162.9$ $Q_{Cu} = 181.7$	— — —	1 073–1 223	IIa(ii), p.c	264

(a) $\log A = -0.8649 + 0.0829\, C_{Al}$, $Q = 44.27 + 0.14\, C_{Al}$ } least squares fit to the data of reference 153.

Al	Fe						
9		2.7×10^{-1}	188.0	—	1 193–1 483 (Disordered)	IIa	18
17		3.6×10^{-3}	142.4	—			
25		7×10^{-2}	167.1	—			
33		7.3×10^{-3}	129.8	—	1 373–1 483 (Disordered)		
33		2.1×10^4	290.6	—	1 073–1 273 (Ordered)		
41		1.5×10^3	305.2		1 073–1 193		
0–~52	(α)	30.1	234.5	—	1 223–1 373	IIa(ii)	120
0–15	—	1.6	306	—	1 048–1 173	Ion impl. c(x) via NRA	283
Al	H						
	0–sol. limit	0.11	110.95	—	633–873	IIIb(ii)	19
Al	He						
~100	V. small	3.0	152.8	—	—	IIIb(ii)	105
Al	Li						
	0–sol. limit	4.5	139.4	—	690–870	IIa(ii)	20
(α-phase *Al*Li)	0.155	119.2	—	673–873	Electrochem. method		293
Al	Mg						
	0	1	129.8	—	523–713	IIa	157
	0–10	4.4	140.3	—			
0–20		12	143.6	—	623–693		
β phase		2.4×10^{-6}	56.9	—	598–698	IIc	213
γ phase		9.9×10^{-1}	117.6	—			

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Al	Mg						
—	0	0.42	125				
—	1	0.49	124	@ 0.101 Mpa.			
—	2	0.61	127	Data also at	690–818	IIa(i), p.c.	273
—	3	0.32	122	2.2 and 3.3 Gpa.			
—	4.06	0.45	122				
Al	Mn						
	0.02–0.15	—	—	Figure 13.14	873–923	IIa(iii)	21
Al	Na						
	0–0.002	1.1	134.0	—	823–923	IIIb(i)	22
Al	Nb						
33	67	2×10^{-3}	230.3	—	1 427–1 773	IIa	222
25	75	2.5	366.3	—			
Al	Ni						
0–0.7		1.87	268.0	—	1 373–1 553	IIa(ii)	23
			$10^{11}\bar{D}$ @				
		1 223	1 273 1 323	1 373 1 423 K			
0.7	—	—	2.2 —	11.0 —			
5.0	—	1.5	3.0 7.9	16.0 37.0	$Q \sim 234$		
10.0	(σ-phase)	2.4	3.8 11.5	24.0 55.0			
14.0	—	—	4.9	33.0 —			
25.0	(ε-phase)	—	6.3 29.5	36.0 116.0	$Q \sim 266$	IIIa(i)	288
38.0	(δ-phase)	—	62.0	270 —	$Q \sim 208$		
$\bar{D}(\delta)$ varies rapidly with composition, with minimum close to the stoichiometric composition (50%). Max Q 60 @ 45% Al, decreasing to 44 @ 36%, 32 @ 53%.							
0–10.2	—	1.3	257	—	1 273–1 473	IIa(i), p.c.	157
—	0	$\ln A = -3.1 \times 10^{-2} Q$	284[a]	—	1 273–1 573	IIa(i), p.c.	313
—	16	−4.49	258	—	1 273–1 573		
Al	Pu						
3–9.1	(δ)	2.25×10^{-4}	106.8		623–790	IIa(ii)	186
Al	Si						
	0–0.5	0.346	123.9	—	617–904	IIa(ii)	224
	0–0.5	2.02	136.1				
		$A_{Si} = 3.95$	$Q_{Si} = 140.1$		753–893	IIa(i)	24
		$A_{Al} = 5.07$	$Q_{Al} = 143.1$				
	0–0.7	—	—	Figure 13.15	723–853	IIa(iii)	21 and 25
Al	Ti						
2.0	(β)	1.4×10^{-5}	91.7	$\bar{D}$ increases	1 256–1 523		
12.0		9.0×10^{-5}	106.8	linearly with c			
10.0	(α)	1.6×10^{-5}	99.2		1 107–1 173	IIa(i)	26
				$D_{Al} = 14.11 \times 10^{-9}$			
				$D_{Ti} = 4.61 \times 10^{-9}$	1 523		
Al	Zn						
—	0–4.49	0.27	118		383–433	X-ray analysis 0° g.b. depletion	272
—	0	0.406	124		723–881	IIa(i), p.c.	277
—	3.5	0.280	121				

Measurements also at 2 and 3 Gpa pressure.

$10^{11} \times \bar{D}$ @ 330°C	360°C	400°C	440°C	485°C	540°C		
~0	1.84	3.98	12.7	49.2	149	610	
9.0	1.95	4.85	19.3	69.6	174	610	
18.1	3.64	6.12	20.0	74.8	2.2	—	27
37.6	..	1.10	—	51.1	—	—	

To very good approximation $D_{Zn} \cdot \bar{D}/c_{Al}(c_{Al}$ = fractional at. conc.)

(a) $\tilde{Q}$ decreases linearly with increase in concentration over this range.

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Al	Zr						
8		9.2×10^{-3}	169.1	—			
10		2.3×10^{-2}	179.2	—			
12		5.2×10^{-2}	189.2	—	1 373–1 573		
14		7.6×10^{-2}	192.2	—			
16		8×10^{-2}	192.2	—	1 433–1 573	IIa(i)	223
	Al_3Zr_5	9.2	283.0	—	1 373–1 573		
	Al_2Zr_3	3.4	272.1	—	1 273–1 573		
	Al_3Zr_4	1.6×10^{5}	382.3	—	1 273–1 573		
As	Fe						
0.6–4.6		4.3	219.8	— (α)	1 223–1 653	IIa(i)	255
		0.58	246.6	— (γ)			
Au	Cu						
	10–90	—	—	Figures 13.12 and 13.13	1 006–1 130	IIa(i)	160
'Au Cu'	50	2.36×10^{-6}	57.1	(Disordered)	823–973	IIa(i)	167
		7.94×10^{-8}	44.9	(Ordered)	573–623		
		$10^{10}\tilde{D}$	$10^{10}D_{Au}$	$10^{10}D_{Cu}$			
1.25	—	1.84	1.8	4.2			
2.50	—	2.10	2.0	4.5			
5.0	—	2.70	2.4	6.4			
7.48	—	3.41	2.8	9.0	1 133	IIa(i)	267
12.44	—	5.40	3.1	16.9			
14.25	—	6.30	2.5	22.5			
17.43	—	8.20	3.0	25.2			
—	0.5	8.99×10^{-3}	133.1				
—	4.2	1.24×10^{-2}	135.9				
—	7.2	1.56×10^{-2}	138.0				
—	11.2	2.17×10^{-2}	140.9				
—	14.6	2.99×10^{-2}	143.7				
—	21.8	5.36×10^{-2}	148.9	—	659–827	Electro-chemical method	280
—	28.3	8.91×10^{-2}	153.5				
—	38.6	0.214	161.1				
—	55.3	0.828	173.2				
—	63.9	1.690	179.4				
—	79.0	6.092	190.7				
Au	Fe						
	0–18.3	1.16×10^{-4}	102.2	—	1 023–1 273	IIa(ii)	28
Au	H						
		2.08×10^{-3}	20.8	—	523–1 073	Ib	29
Au	In			$\tilde{D}$ at 142°C $\tilde{D}$ at 151°C ($\times10^{-12}$)			
3				0.47 24.0			
33	($Au In_2$)			7.0 29.0			
50	(Au In)			2.6 6.6	—	IIa(i)	30
69	($Au_9 In_4$)			5.8 9.8	(Values of D_{In} listed,		
80	(Au_4 In)			0.49 0.68	calculated assuming		
91				0.24 0.28	$D_{Au} \ll D_{In}$)		
Au	Ni						
	2	4.3×10^{-2}	173.3				
	10	3.9×10^{-2}	173.8				
	20	9.5×10^{-2}	183.0				
	30	7.8×10^{-2}	183.8				
	40	2.2×10^{-2}	175.8				
	50	1.3×10^{-2}	177.5		1 123–1 248	IIa(i)	31
	55	5.9×10^{-3}	174.6				
	60	6.8×10^{-2}	204.3				
	65	1.4×10^{3}	305.6				
	70	2.0×10^{7}	402.8				
	75	6.2×10^{8}	439.6				
	98	1.8×10^{4}	356.7				

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Au	Pb						
0–~0.09	0	0.35	58.6	—	386–573	IIa(ii)	32
Au	Pd						
	0–17.1	1.13×10^{-3}	156.6	—	1 000–1 243		33
~50		3.2×10^{-4}	152.8	—	873–1 323	IIa	152
Au	Pt						
98		0.62	228.6				
96		1.0	234.5				
94		0.73	231.9				
92		0.67	231.9				
90		0.60	231.1				
88		0.58	231.1				
86		0.53	230.7	—	1 198–1 328	IIa(i)	34
84		0.52	231.1				
82		0.47	230.7				
80		0.43	230.3				
2–8		0.37	262.1				
95		$A_{Au}=0.32$	$Q_{Au}=190.9$				
		$A_{Pt}=0.09$	$Q_{Pt}=226.1$				
B	Fe						
0–0.009 5	(α)	10^6	259.6	—	973–1 108	IIIa(ii)	35
0–0.02	(γ)	0.002	87.9	—	1 223–1 573	IIIa(ii)	36
	(Analysis of 'Fe' for both experiments (in wt.%) 0.0038**B**, 0.43C, 1.64Mn, 0.02**P**, 0.019S, 0.37Si, 0.04Cr, 0.01Ni, 0.01Mn)						
Ba	H	4×10^{-3}	19.0	—	473–893	IIa(ii)	250
Ba	U						
0–sol. limit	(γ)	0.112	170.8		1 123–1 313	IIc	85
Be	Cu						
0–~15	(α)	0.19	173.8	—	823–1 157		
~33	(β)	0.084	115.1	—	923–1 157		
~48	(γ(β'))	0.054	129.8	—	823–1 157	IIa(i)	37
~75	(δ)	0.0012	138.2	—	823–1 157		
~33	(β)	$A_{Be}=0.035$	$Q_{Be}=121.4$				
		$A_{Cu}=0.045$	$Q_{Cu}=104.7$				
Be	Fe						
	0–0.2	1.0	226.1	—	1 073–1 373	IIa(i)	38
		Very little variation of $\tilde{D}$ with c					
Be	H						
		2.3×10^{-7}	18.42	—	473–1 273	IIIb	86
Be	Mg						
0–sol. limit		8.06	157.0	—	773–873	IIIa(i)	212
Bi	Pb						
0–2.0		0.018	77.0	—	493–558	IIa(i)	39
C	Co						
		8.72×10^{-3}	149.3	—	723–1 073	IIa(i). p.c.	158
~0.1–0		0.31	153.7	—	1 073–1 673	IIIa(i)	216
C	Co Fe						
	78.5	0.472	157.0	—	1 123–1 373	IIIb(ii)	41
0.48	89.4	0.442	157.0	—	1 123–1 385		
0–0.7 (wt.%)	0, 5.8, 10.6, 20.2 (γ)	$0.04+0.08\,c$; $0.04+0.08\,c$; $0.03+0.1\,c$; $0.03+0.06\,c$	131.3; 127.7; 125.2; 120.8		1 273–1 473	IIa(i)	146
		(c = wt.%C)					
C	Fe						
0–0.1	(α)	3.94×10^{-3}	80.2	—	313–623	Various	215
γ-range	$D=4.53\times10^{-3}[1+y_c(1-y_c)8339.9/T]\exp[-(T^{-1}-2.221\times10^{-4}\times17\,767-26\,436y_c)]$						
	$y_c=x_c/(1-x_c)$.			x_c = mol fraction of C			42
α-range	$\text{Log}\,D=-0.9064-0.5199\chi+1.61\times10^{-3}\chi^2$				233–1 140	Combined data, several sources	40
	$\chi=10^4/T$						

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
C	**Fe Mn**						
0.4 (wt.%)	(γ) 0	0.07	131.3	—	1 273–1 473	IIa(i)	148
	(γ) 1.0	0.08	132.3				
	(γ) 12.1	0.19	141.9				
	(γ) 19.2	0.41	151.1				
C	**Fe Ni**						
0–0.7 (wt.%)	(γ) 0	$0.04+0.08\ c$	131.3	—	1 273–1 473	IIa(i)	147
	(γ) 3.9	$0.3+0.1\ c$	129.8				
	(γ) 9.2	$0.03+0.1\ c$	127.9				
	(γ) 17.3	$0.02+0.1\ c$	124.8				
		(c = wt.%C)					
0–0.1 wt.%	(γ) 23	0.322	148.1	—	1 123–1 373	IIIa(i)	56
	(γ) 40	0.20	139.8				
	(γ) 60.4	0.296	145.2				
	(γ) 70	0.372	148.5				
	(γ) 80	0.680	156.0				
	(γ) 100	0.366	149.3				
C	**Fe Si**						
Sol. soln range	(γ) 0–2.35	—	—	Figure 13.27	1 153–1 223	IIc	145
C	**Mo**						
Sol. soln range		0.034	171.7	—	2 053–2 243	IIIa(i)	198
C	**Nb**						
0.3–1.0		1.8×10^{-2}	159.1	—	1 873–2 393	IIIb(ii)	128
C	**Ni**						
		0.12	137.3	—	873–1 673	IIa(ii), p.c.	43
0–0.1 wt%	0.366	149.3	—	1 123–1 373	IIIa(i)	56	
C	**Re**						
2 or 3–0		0.1	221.9	—	1 503–2 003	IIIb(ii)	205
C	**T**						
		6.7×10^{-3}	161.6	—	463–2 953	Various	249
C	**Th**						
~7.2		—	~159.1	7.4×10^{-9} (1 273); 2.8×10^{-8} (1 373); 5.7×10^{-8} (1 473)		IIIa(i)	44
100–400 p.p.m.	(β)	0.022	113.0	—	1 713–1 953	IIa(ii)	159
C	**Ti**						
0.14–sol. limit	(α)	5.06	182.1	$\tilde{D}$ indep. of conc.	1 009–1 108	IIc	45
	(β)	6×10^{-3}	94.6	—	1 613–1 873	IIa(ii)	252
C	**V**	8.8×10^{-3}	116.4	—	333–2 098	Various	247
C	**Zr**						
	(β)	0.004 8	111.8	—	1 173–1 523	IIa	209
Cd	**Cu**						
0–0.5		3.5×10^{-3}	122.3	—	773–1 123	IIa(ii)	6
Cd	**Pb**						
0–1.0		1.85×10^{-3}	64.5	—	440–525	II	46
Cd	**Hg**						
	0–4.0	2.57	82.1	—	429–475	III(ii)	46
Ce	**Mg**						
Sol. soln range in Mg		450	175.8	—	773–871	IIc	210 and 174
Ce	**Pu**						
3.74–7.17	(δ)	1.31×10^{-2}	123.9	—	676–801	IIa(ii)	187

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Ce	U						
0–sol. limit	(γ)	3.92	278.0	—	1 073–1 273		
Co	Cr						
	0–15.2	0.084	253.7	—	1 273–1 573	IIa(ii)	47
	0–40	0.443	266.3	—	1 273–1 643	IIa(iii)	48
		(D reported f(c), but concentration dependence very slight)					
Co	Cu						
0.1		0.6	213.5	—	800–1 073	IIa(i)	256
2	(wt%)	5.7	242.8	—			
—	0–5	~1.0	~275	—	1 158–1 273	IIIa(i), p.c.	274
Co	Fe						
5–70 (b.c.c.)			*See* Figure 13.16a		993–1 228	IIa(i), p.c.	318
5–95 (f.c.c.)			*See* Figure 13.16b		1 273–1 573		
10		1.5×10^{-3}	219.0	—	1 273–1 673	IIa(i)	242
20		2.9×10^{-3}	215.2	—			
30		4.4×10^{-3}	212.3	—			
40		5.8×10^{-3}	216.5	—			
50		7.0×10^{-3}	215.2	—			
60		8.8×10^{-3}	217.3	—			
70		11.5×10^{-3}	218.1	—			
80		12.0×10^{-3}	218.1	—			
90		13.1×10^{-3}	219.0	—			
Co	H						
	5 Atm.	8.3×10^{-3}	49.4	—	673–823(α)	Ic	195
		3.4×10^{-2}	57.8	—	473 × 673(ε)		
Co	Mn						
	5	7.79	296.2	(Ferro)	1 133–Tc		
	5	0.781	273.2	(Para)	T_c–1 423		
	10	3.07	284.2		1 133–1 423	IIa(i)	225
	20	0.70	257.2				
	30	0.721	248.2				
	40	0.627	241.2				
	33	$A_1 = 0.22$	$Q_1 = 263$				
		$A_2 = 0.98$	$Q_2 = 229$				
Co	Mo						
	0–10	0.231	262.9	—	1 273–1 573	IIa(ii)	47
	0–15	2.48	294.8	—	1 073–1 573	IIa(i)	226
Co	Ni						
10–90		$\tilde{D} = 1.58 \exp(-0.95N) \exp(-278.3/RT)$			1 433–1 673	IIa(i), p.c.	242 and 161
5–95		$\tilde{D} = 0.22 \exp(-1.14N) \exp(-256.2/RT)$			1 263–1 423		
		N = mol fraction of Co					
		A_{Co}	Q_{Co}	A_{Ni}	Q_{Ni}		
15		0.388	267	0.0493	232	IIa(i), p.c.	161
20		0.410	270	0.136	244		
25		0.433	273	0.372	256	1 263–1 423	
30		0.457	276	1.02	268		
Co	O						
		67.8	241.2	—	1 323–1 573	Intern. oxid.	309
Co	Pd						
10				13.7×10^{-11}	1 423	IIa(i)	144
20				25.6			
30				55.0			
40				120			
50				145			
60				120			
70				70.7			
80				28.2			
90				13.9			

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Co	Pt						
	0–100		Figure 13.17	—	1 398–1 573	IIa(i)	218
Co	Ti						
	4–8	15	280.5	—			
(Co_3Ti)	21	5.3×10^{-2}	167.5	—	1 173–1 413	II	227
(Co_2Ti)	30–32	0.28	217.7	—			
(CoTi)	46–50	4.4×10^{-4}	173.3	—			
βTi	90–95	67	207.2	—	973–1 123		
Co	V						
	0–17	0.021	221.9	—	1 373–1 573	IIa(ii)	47
Co	W						
	0.5	0.008	238.2	—	1 373–1 573	IIa(ii)	47
Cr	Fe						
10–20	(α)	1.48	229.9	$\tilde{D}$ indep. of c (In the range 10–1%, $\tilde{D}$ increases by ~30%) $D_{Cr} \sim 1.5 D_{Fe}$	1 096–1 713	IIa(i)	49
37				80×10^{-10}			
42				56×10^{-10}			
52				27.8×10^{-10}			
62	(α)			11.7×10^{-10}	1 523	IIa(i)	50
72				7.1×10^{-10}			
81				4.9×10^{-10}			
91				4.6410^{-10}			
0–71	(γ)	0.001 2	218.6	—	1 173–1 473	IIa(ii)	47
0	—	1690	299.3	—	1 044–1 124		
5	—	824	292.0	—	1 049–1 124		
10	—	221	279.2	—	1 039–1 124		
15	—	256	280.4	—	984–1 124	IIa(i), Fe s.c.	258
20	—	60	268.9	—	974–1 124		
25	—	15	258.7	—	974–1 124		
Cr	N Ti						
		1.6×10^{-2}	115.1	—	331–463	Vb	129
—	0	0.009 6	119.3	—	1 273–1 673	Internal	
—	1 Atm. press. 0.5	0.009 0	118.1	—		nitridation	
—	1 Atm. press. 3.0	0.005 4	111.4		1 272–1 673	method	196
—		0.002 5	100.5				
Cr	Nb						
(γ)	2	34.0	409.9	—	1 373–1 897		
Cr_2Nb	34	26.0	393.6	—	1 524–1 897		
	38[a]	24.0	396.9[b]			IIa(i)	140
(α)	90	2.7	385.2	—	1 373–1 897		
	95	0.31	360.1				

(*a*) The compound Cr_2 Nb is reported to have a 5% solubility range.
(*b*) Arrhenius plots not always linear. $\tilde{Q}$ and $\tilde{A}$ derived from measurements at the higher temperatures.

Cr	Ni						
0–12		0.604	257.2	—	1 273–1 573	IIa(ii)	47
Cr	Ni						
0–14	wt.%	0.5[a]	260	—	1 373–1 523	IIa(i), p.c.	311

(*a*) Average values. $\tilde{D}$ increases linearly ~25% over the comp. range.

Cr	Ti						
9	(β)	—	—	3.6×10^{-9} $D_{Ti} = 2.8 \times 10^{-9}$ $D_{Cr} = 3.7 \times 10^{-9}$	1 258	IIa(i)	53
Cr	U						
0–sol. limit	(γ)	0.7	142.4	—	1 173–1 273	IIc	54

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Cu	Fe						
		A_{Cu}	Q_{Cu}	A_{Fe} Q_{Fe}			
ε Sol. soln		6.1	268.0	2.7 265.9	1 173–1 323	IIa(ii)	193
γ Sol. soln		3.6	274.2	8.9 314.0			
(γ-phase)		8.8×10^4	204	—	1 323–1 583	IIIa(i)	24
(δ-phase)		—	—	$5.7 \times 10^{-8(a)}$	1 773		
—	0–2.59	0.54	208.3	—	1 073–1 323	IIIa(ii), p.c.	303
wt.%	0–0.64	0.091	193.2	—	923–1 073		
Cu	Ga						
	0–3	0.58	193.8		973–1 323	IIb	219
	2.5	3×10^{-4}	134.0	—			
	4.9	1.8×10^{-3}	142.4	—			
	7.6	1.6×10^{-2}	154.9	—			
	10.3	1.8×10^{-1}	167.5	—	773–973	IIa(i)	228
	13.1	1.3×10^{-1}	157.0	—			
	15.9	8×10^{-2}	146.5	—			
Cu	H						
	(H) sol. limit	11.31×10^{-3}	38.88	—	720–1 200	IIIb(iii)	162
	(D) sol. limit	7.30×10^{-3}	36.82	—			
	(T) sol. limit	6.12×10^{-3}	36.50	—			
Cu	In						
—	0	0.73	189				
—	1	0.93	188				
—	2	1.2	188				
—	3	1.8	189				
—	4	5.8	195	—	949–1 119		
—	5	9.8	198				
—	6	11	196				
—	7	18	198				
		$10^{10} D_{Cu}$	$10^{10} D_{In}$				
—	0.9	0.71	1.5		1 005		
		4.4	8.85		1 089	IIa(i), p.c.	262
—	1.7	0.62	1.9		1 005		
		1.9	4.8		1 043		
		4.95	11		1 089		
—	2.9	0.24	1.25	—	970		
		0.62	2.9		1 005		
		1.65	7.4		1 043		
		5.4	16.5		1 089		
—	4.6	0.46	1.3		949		
		0.51	2.0		970		
		1.3	5.1		1 005		
Cu	Mn						
	0–28	0.58	177.5	*D* indep. of conc.	913–1 093	IIa	163
—	5	0.37	187				
—	10	0.56	187				
—	15	0.51	183				
—	20	0.53	181				
—	25	0.66	181				
—	30	1.17	186				
—	35	1.33	189				
—	40	2.34	197	—	1 023–1 123	IIa(i), p.c.	243
—	45	10.7	216				
—	50	93.6	241				
—	55	41.0	239				
—	60	2.1	218				
—	65	0.14	198				
—	70	0.07	195				
—	75	0.16	204				
Cu	Ni						
~0	~100	0.4	257.9				
	0–100			Figure 13.18	1 038–1 339	IIa(i)	55
~100	~0	1.4	228.2				
—	0–7	$D = 6.09 \times 10^{-10} \exp(-5.94 N_{Ni})$			1 273	IIa(i), p.c.	299
—	1.05–4.84	$D_{Ni} = 6.11 \times 10^{-10} \exp(-9.08 N_{Ni})$					
		$D_{Cu} = 2.3 \times 10^{-9} \exp(-6.13 N_{Ni})$					

N_{Ni} = mol fraction of Ni.

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Cu	O						
		5.8×10^{-3}	57.4	—	873–1 273	Internal oxid.	197
Cu	Pd						
	50	0.48	224.0	—	1 073–1 323	IIa	152
	0–100	—	—	Figure 13.28	1 204–1 334	IIa(i)	160
Cu	Pt						
0–13.9		0.049	233.2	—	1 313–1 673	IIa(ii)	28
	Small	0.67	233.2	—	1 023–1 348	IIb	244
Cu	Sb						
—	0	0.82	185		919–1 040		
—	1	0.32	174				
—	2	0.094	160				
—	3	0.030	147				
		$10^{14} D_{Cu}$		$10^{14} D_{Sb}$			
—	1	1.8		2.9	1 005	IIa(i), p.c.	281
—	1	3.7		6.1	1 040		
—	1.7	0.5		2.2	970		
—	1.7	1.9		4.05	1 005		
—	1.7	3.7		7.8	1 040		
Cu	Si						
—	0	0.21	187				
—	2	0.27	186				
—	3	0.24	184				
—	4	0.34	183				
—	5	0.36	182	—	998–1 173	IIa(i), p.c.	59
—	6	0.28	181				
—	7	0.19	172				
—	8	0.20	170				
—	9.8	0.13	163				
	α: sol. soln range	11.4	200.3	—	938–1 048	IIc	164
Cu	Sn						
(α)	0–7	$2 \times 10^{-2} \times 10^{0.133 c_{Sn}}$					
			156.1	$D_{Sn} > D_{Cu}$	1 000–1 100	II	16
		(c_{Sn} = at.%Sn)					
—	14.5	9.11	134				
β-phase		$A_{Cu} = 0.258$	$Q_{Cu} = 103$	—	874–993	IIa(i), p.c.	275
		$A_{Sn} = 30.5$	$Q_{Sn} = 144$				
(δ)	20.5	$\{D_{Cu}\}$ $\{D_{Sn}\}$	Figure 13.20	7.7×10^{-10} 3.6×10^{-9} 1.0×10^{-8} 1.1×10^{-7} 1.65×10^{-7} 1.3×10^{-7}	701 714 731 780 818 845	IIc	60
(γ)	15–22	$\{D_{Cu}\}$ $\{D_{Sn}\}$	Figure 13.22	Figure 13.21	979.5	IIa(i)	
(ε)		1.43×10^{-4}	70.8	—	433–493	II	229
(η)		1.55×10^{-4}	64.9	—			
Cu	Ti						
	0	0.693	196	—	973–1 283	IIa(i)	230
	0.5	0.934	199	—			
	1.0	1.41	204	—			
	1.5	1.92	208	—			
3 (α-phase)		1.32×10^{-5}	87.3				
Cu_7Ti_2		7.15×10^{-6}	92.3				
Cu_3Ti_2		1.05×10^{-4}	116				
Cu_4Ti_3		2.25×10^{-3}	142	—	1 023–1 123		278
CuTi		2.05×10^{-1}	166				
$CuTi_2$		$3.37–10^{-5}$	112				
β-phase		5.76×10^{-2}	182				

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Cu	**Zu**						
	1	0.056	167.5				
	5	0.062	167.5	—	1 053–1 188		
	10	0.083	165.4				
(α)	16	0.095	159.1			IIa(i)	61
	20	0.09	152.9				
	25	0.031	136.1	—	997–1 188		
	28	0.016	124.3				
		D_{Cu} and D_{Zn}—Figures 13.23, 13.24 and 13.25					
—	0	0.412	196				
—	5	0.375	189				
—	9	0.285	182		1 105–1 223	IIa(i), p.c.	266
—	15	0.614	184[a]				
	10	0.13	170.8				
	15	0.21	170.8				
	20	0.36	170.8				
(α)	28	1.7	172.9	—	973–1 183	IIIa(i)	62
	28 D_{Zn}	2.1	172.5				
	28 D_{Cu}	0.81	178.8				
(β)	46	—	—	$D_{Zn}/D_{Cu}=2.4$–3.6	873–1 073		
(β)	48	0.0069	78.7	(Disordered)	753–983	IIa	
		1 440	150.7	(Ordered)	591–720		
(β)	44–48	0.018–0.013	83.3–76.2	—	773–1 073	IIa(i)	63
	59	2.45×10^{-2}	98.0				
	60	2.44×10^{-2}	95.9				
	6I	1.71×10^{-2}	91.7				
	62	2.45×10^{-2}	91.7	—	648–923		
(γ)	63	1.14×10^{-2}	84.2				
	64	0.99×10^{-2}	80.8				
	65	0.62×10^{-2}	74.1				
	65.5	0.19×10^{-2}	64.9	—	698–923	IIIa(i)	64
	66.5	0.28×10^{-2}	64.1	—	798–923		
				D_{Zn}/D_{Cu}			
	65–66	—	—	9.4	648–748		
	67	—	—	11.4	798		
(γ)	68	—	—	8.6	848		
	68	—	—	5.7	923		
(ε)	79–86	*See* Figure 13.36		—	523–673	IIa(i)	251

(*a*) Results also for *D*'s at pressures 2 and 3 Gpa.

Fe	**H**						
(α)		7.5×10^{-4}	10.13	—	230–1 100	Various	319
	At $T<\sim200$°C $\tilde{D}$ is usually less than expected from extrapolation of higher T results and apparently depends on sample history. *See* reference 319						
(γ)		1.85×10^{-2}	50.02	—	1 184–1 667		65
(δ)		1.09×10^{-3}	12.54	—	1 667–1 811		66
Fe	Mn						
	5	5.95	314.0	—			
	10	3.04	303.1	—			
N							
	15	3.37	305.2	—			
	20	2.89	301.0	—			
	25	2.83	296.8	—			
(γ)	30	2.53	295.2		1 283–1 523		
	35	3.12	298.9	—			
	40	2.44	294.8	—			
	45	2.17	291.0				
	50	1.96[b]	286.0	—		IIa(i)	166
	55	2.04	289.3	—			
	36.4	—	—	$D_{Fe}=3.48\times10^{-12}$, $D_{Mn}=6.22\times10^{-22}$	1 283		
	38.0	—	—	$D_{Fe}=5.29\times10^{-12}$, $D_{Mn}=1.55\times10^{-11}$	1 363		
				$D_{Fe}=9.07\times10^{-11}$, $D_{Mn}=2.42\times10^{-10}$	1 523		
	41.2	—	—	$D_{Fe}=3.36\times10^{-11}$, $D_{Mn}=8.04\times10^{-11}$	1 443		

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* kJ mol^{-1}	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Fe	Mn						
	5	7.2×10^{-2}	250.8	—	1 123–1 573	IIa(i)	231
	10	1.75×10^{-2}	263.8	—			
	15	3×10^{-1}	269.6	—			
	20	1.63×10^{-1}	262.1	—			
	25	7.2×10^{-2}	248.7	—			
	30	1.20×10^{-1}	251.2	—			
Fe	Mn C (wt%)						
(γ)	4 0.02	0.57	277.2	—	1 323–1 723	IIa(i) and (ii)	67
	14 0.02	0.54	273.8				
	4 0.51	1.25	256.2	—	1 273–1 523		
	14 0.52	1.25	255.4				
	Empirically $\tilde{D}$ may be represented (±20%) over the ranges 0–20% Mn, 0–1.5 wt% C by $\tilde{D} = (0.486 + 0.011$ wt% Mn$)(1 + 2.53$ wt% C$) \exp(-66\,000/RT)$						
(γ)	0–60	—	—	Figure 13.26	1 473	IIa(i)	67
Fe	Mo						
(γ)	0–0.59	0.068	247.0	—	1 423–1 533	IIa(ii)	89
		(Addition of 0.4 wt% C increases *A* to 0.091)					
(α)	1.9–3.6	3.467	241.6	—	1 203–1 533	IIa(ii)	
	α sol. soln range	10	251.2	—	1 063–1 458	IIc	52
Fe	N						
(α)		4.88×10^{-3}	76.83	—	226–1 183	Combined data, several sources	68
(γ)	0–sol. in eq. with 0.95 atm. N_2	0.91	168.6	—	1 223–1 623	IIIa(i) and IIIb(ii)	70 and 71 and 69
Fe	Ni						
—	10.4–15.5	—	—	3.6×10^{-15}	1 073	IIa(ii), p.c.	270
		—	—	2.3×10^{-16}	1 030		
—	10	4.79×10^{-2}	247.8				
—	20	8.22×10^{-2}	250.3				
—	30	0.121	251.1				
—	40	0.109	245.3				
—	50	0.394	254.9	—	1 193–1 573	IIa(i), p.c.	141
—	60	1.92	270.0				
—	70	2.89	273.7				
—	80	3.03	274.6				
—	90	3.11	277.1				
	0–100	Figure 13.31					
	31–33	$A_{FE} = 3.6$	$A_{NI} = 1.6$	—	1 403–1 629	IIa(i)	160
		$Q_{FE} = 286.8$	$Q_{NI} = 303.5$	—			
		Diff. of C			0–0.2%C		
—	20	~0.1	~138				
—	40–60	~0.01/~0.05	~117				
wt.%	70	~0.05	~128	—	1 223–1 423	IIa and IIIa(ii)	302
—	80–90	~0.2/~0.4	~155				
—	100	~0.15	~138				

Fe	Ni	C (wt.%)	*A*	*Q*	*D*	K		
(γ)	4	0.03	0.44	283.4		1 370–1 723	IIa(i) and(ii)	72
	16	0.03	0.51	281.8				
	4	0.6	0.46	274.27		1 323–1 573		
	16	0.6	0.42	27.0				
	Empirically, $\tilde{D}$ may be represented (±20%) over the ranges 0–20 Ni, 0–1.5 wt% C by $\tilde{D} = (0.344 \pm 0.012$ wt% Ni$) \times (1 + 2.3$ wt% C$) \exp(-67\,500/RT)$							

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Fe	O						
[a]	Sol. soln range	5.75	169.1	—	γ-range	Internal oxidation	168
	Sol. soln range	3.7×10^{-2}	98.0	—	α and δ range		
[b]	Sol. soln range	0.4	167.1	—	973–1 123(α)	Internal	201
[a]Fe + 0.1%Al. [b]Fe + 0.07%Si.							
Fe	P						
(α and δ)	Sol. soln range	~2.9	~23a3	—	1 125–1 148 and 1 683–1 731	IIa(i)	79
(γ)	Sol. soln range	28.3	292.2	—	1 523–1 623		
Fe	Pd						
10		—	232.8	—	1 373–1 523	IIa(i)	253
20		—	228.2	—			
30		—	227.8				
40		—	227.8	—			
50		—	232.4	$D_{Fe} > D_{Pd}$			
60		—	240.7				
70		—	242.4	—			
80		—	270.9	—			
90		—	273.8	—			
Fe	S						
(α)	Sol. soln range	1.68	204.7	—	1 023–1 173	IIIa(i)	73
(α and δ)	Sol. soln range	1.35	202.6	—	1 023–1 173 1 673–1 723	IIa(i)	73 and 74
(γ)	Sol. soln range	2.42	223.6	—	1 473–1 625	IIa(i)	74
Fe	Sb						
	0	2.6×10^{-1}	264	—	973–1 223	IIIa(i)	254
	1	6.4×10^{2}	249	—			
	2	2.2×10^{2}	237	[a] —			
	3	9.3×10^{-3}	228	—			
	4	4.3×10^{-3}	220	—			

(a) D is a little lower ($\approx \times 2$) at temperatures below the magnetic transformation at 765°C.

Fe	Si						
()	4.57.1	0.44	201.0	—	1 3681 623	IIa(i)	75
(α)	0–4.21[a]	$0.735 \times (1 + 0.124c_{Si})$	219.9	—	1 173–1 673	IIa(i)	169
	8.35	1.82	215.3	—	1 173–1 373	IIa(i)	171
	8.69	1.87	215.1	—			
	9.04	1.77	214.0				
(α)	9.38	1.62	212.8	—			
	9.73	1.52	211.8	—			
	10.07	1.55	211.6	—			
	10.41	1.66	212.1	—			
	~0	8	249.1	(Extrapolated)			
(α)	4	17	249.1	—	1 073–1 673	IIa(i)	170
	5	17	247.4				
	8	35	248.7				
(α Ferro.)	3 12	500	286.8		673–873 (Ferromagnetic)	—	172
(γ)	0- 2	—	—	4×10^{-10}	1 479	IIa(ii)	75
		—	—	1.7×10^{-9}	1 566		

(a) +1.4%V to stabilize the α-phase.

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Fe	Sn						
—	0–1.6 wt.%	8×10^7	159.9	α-phase	1 033–1 235	IIa(ii), p.c.	260
—	0–0.3 wt.%	2.32	185.5	γ-phase	1 235–1 473		
α- and δ-phase		0.931	221		1 183–1 680	IIIa(i), p.c.	297
γ-phase		5.0×10^{-3}	136		1 273–1 580		
α-phase	1	$\ln A = 6.5 \times 10^{-2} \bar{Q}$	228[a]		1 073–1 373	IIIa(i), p.c.	81
	8	−13.19	221				

(a) $\bar{Q}$ decreases linearly with increase in Sn composition over this range.

Fe	Ti						
(α)	~0.7–3.0	3.15	247.9	—	1 348–1 498	IIc	77
(γ)	0~0.7	0.15	251.2	—	1 348–1 498	IIa(i)	
	2	68	261.3	—	973–1 573	IIa	76
5	(β)	0.60	188.4	—	1 173–1 573		
10	(β)	0.77	193.0	—	973–1 573		
15	(β)	3.6	214.4	—	973–1 323		
66.7–75	—	—	—	2.94×10^{-12}	1 323	IIa(ii), p.c.	300
($TiFe_2$)		—	—	7.38×10^{-12}	1 373		
				$D_{Fe} = 6.34 \times 10^{-12}$	1 323		
				1.56×10^{-12}	1 373		
				$D_{Ti} = 1.24 \times 10^{-12}$	1 323		
				3.3×10^{-12}	1 373		
Fe	U						
0–sol. limit	(γ)	1.3	134.0	—	1 063–1 273	IIc	54
Fe	V						
(α) atm.	0.7	0.61	267.1	—	1 223–1 523	IIa(i)	78
	5.0	3.9	238.2				
	10.0	1.1	224.0				
	15.0	0.70	219.8				
	20.0	0.71	221.1				
	25.0	0.63	221.1				
	30.0	0.59	222.3				
	10.0(1, 2 and 40 kb pressure)			Figure 13.29			
(γ)	0.7(1, 20 and 40 kb)			Figure 13.30	1 223–1 573		
(γ)	2.0(40 kb)	—	—	5.8×10^{-12}	1 373		
				2.5×10^{-11}	1 435		
				2.9×10^{-11}	1 474		
				1.1×10^{-10}	1 548		
				2.6×10^{-10}	1 623		
(γ)	3.0(40 kb)	—	—	6.3×10^{-12}	1 373		
				2.0×10^{-11}	1 435		
				3.2×10^{-11}	1 474		
				1.6×10^{-10}	1 548		
				1.4×10^{-10}	1 565		
				2.8×10^{-10}	1 623		
Fe	W						
0–0.13		11.5	594.5		2 200	IIIb(ii)	82
	0–1.3	—	—	3.7×10^{-10}	1 553	IIa	83
	0–1.2	—	—	2.4×10^{-9}	1 603		
	0–3.4	—	—	1.0×10^{-9}	1 603		
Fe	Zn						
8.5		2.97×10^{-3}	64.5		741–798	IIa(i)	232
9.0		7.88×10^{-3}	72.4				
9.5		1.39×10^{-2}	80.4				
10.0		5.53×10^{-3}	79.5				
10.5	(δ_1)	2.82×10^{-3}	80.4				
11.0		1.02×10^{-3}	76.2				
11.5		5.81×10^{-4}	74.1				
12.0		6.98×10^{-4}	74.9				
12.5		1.26×10^{-3}	75.8				
13.0		8.21×10^{-3}	78.3				
21.5–22.5	(Γ_1)	2.04×10^{-4}	80.4				
31–32	(Γ)	1.05×10^{-3}	92.1				

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Fe	**Zn**						
0–6	(ζ)	2.28×10^{-2}	83.3		513–633	IIa	233
—	0	60	262.6				
—	2	38	256.2				
—	4	19	247.5				
—	6	11	239.9	—	1 068–1 169 [a]	IIIa(i), s.c.	282
—	8	6.2	232.9				
—	10	3.9	226.4				
—	12	2.0	218.1				
(a) At $T < 1068$, D's decrease below extrapolation of high T Arrhenius line.							
Ga	Pu						
3–7.9	(δ)	1.3	156.5	($\tilde{D}$ indep. of conc.)	623–790	IIa(ii)	184
0.48–2.6	(ε)	5.3×10^{-4}	55.3	—	833–913	IIa(i)	185
2.5–6.5	(δ)	0.098	138.2	—	673–807	IIa(i)	214
Ga	Ti						
Sol. soln range	(α)	4.4×10^{-4}	181.7	—	873–1 133		
25	(Ti_3Ga)	7.4×10^{-5}	183.4	—			
Ge	**H**						
	Range of c in eq. with H_2 gas over p, range 10–76 cm Hg	2.72×10^{-3}	364	—	1 073–1 183	Ic	84
Ge	**He**						
~100	V. small	6.1×10^{-3}	67.0	—	1 068–1 145	Ic	106
Ge	Nb						
66.7	33.3	6.4×10^{-2}	161	($NbGe_2$)			
40	60	2.27	282	(Nb_3Ge_2)	1 243–1 723	IIIa(i), p.c.	268
37.5	62.5	0.628	238	(Nb_5Ge_3)			
H	Mo						
		1×10^{-2}	58.6		1 173–1 773	Various	194
H	Nb						
0.2–4.3		5×10^{-4}	10.24	—	273–573	Va	80
H	Ni						
		6.44×10^{-3}	40.2	—	297–1 393	Various	90
H	Sol. soln range	7.04×10^{-3}	39.5	—			
D		5.27×10^{-3}	38.7	—	673–1 273	IIIb(ii)	162
T		4.32×10^{-3}	38.1				
H	Pd						
		2.9×10^{-3}	22.2	—	~230–1 100	Combined data, several sources	319
		Permeation of H through Pd very much affected by sample history, — contamination, etc. See references 91–95					
H	Pt						
500 torr		6×10^{-3}	24.7	($D_H/D_D = 1.16$)	873–1 173	Ic	203
H	Si						
$0-\sim 10^{-8}$		9.4×10^{-3}	46.0	—	1 363–1 473	Ic	106
H	Ta						
0.2–4.3		4.4×10^{-4}	13.52 [a]	—	250–573	Va	80
		2.0×10^{-6}	3.86	—	91–200	Combined data, several sources	319
H	Th						
Sol. soln range		2.92×10^{-3}	40.82	—	573–1 173	IIIa(i) and IIIb(ii)	96

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
H	Ti						
	(α)	2.8×10^{-5}	23.85	—	293–500		97
		3.3×10^{-2}	57.74	—	500–1 100		
	(β)	2.46×10^{-3}	31.58	—	1 160–1 490		317 and 298
H	U						
(n.s.)	(α)	0.0195	46.47	—	663–903	IIIb(ii)	98
	(β)	—	—	7.3×10^{-5}	973	IIIb(ii)	
				1.0×10^{-4}	997		
(n.s.)	(β)	3.3×10^{-4}	15.07	—	971–1 023	IIIb(ii)	99
	(γ)	1.5×10^{-3}	47.73	—	1 073–1 243	IIIb(ii)	
	(γ)	1.9×10^{-2}	48.5	—	1 020–1 250	IIIa(i)	316
H	V						
		3.1×10^{-4}	4.34	—	143–573	Combined data, several sources	319
H	W						
10^{-8}–600 torr		4.1×10^{-3}	37.68	—	1 103–2 493	IIIb(ii)	206

(*a*) True diffusion coefficients. Apparent *D*'s may be much smaller, with higher *Q* and *A*, due to surface effects. *See*, for example, references 87, 176, and 173.

H	Zn						
		$\perp c$ 8.5×10^{-2}	18.62	—	298–344	s.c.	315
H	Zr						
	(α)	4.0×10^{-2}	56.9	—	330–970		314 and 100
40–200 p.p.m.	(α)[a]	7.0×10^{-3}	44.59	($D_{\parallel c} \approx 2D_{\perp c}$)	548–973	IIa(ii)	101
Sol. soln range	(α Zircalloy 2)	2.17×10^{-3}	35.09	—	533–833	IIIa(i)	102
0–41	(β)	5.32×10^{-3}	34.83	(D indep. of c)	1 033–1 283	III(i)	103
	(β)	7.37×10^{-3}	35.76	—	1 143–1 373	IIa(i)	100

(*a*) No significant difference in results for Zircalloy 2 and Zircalloy 4 from those for pure Zr. Values quoted are means of all measurements.

He	Mg						
$0-\sim 6.10^{-9}$		60.0	150.7	—	673–848	IIb(ii)	104
He	Si						
$0-\sim 4.10^{-10}$		0.11	121.4	—	1 443–1 480	Ic	106
He	Th						
0–0.13	(α)	10^{-3}–10^{-4}	159.1	—	1 173–1 723	IIIb(ii)	107
He	Ti						
16	(α)	1.1×10^{-9}	67.4	—	888–993	IIb(ii)	117
Hf[a]	N						
(α)	v. low	2.42×10^{-2}	242.3	—	823–1 173	IIa(ii), p.c.	305
(β)	v. low	8.0×10^{-3}	124.3	—	2 103–2 383	IIa(ii), p.c.	307

(*a*) Hf+3 wt.% Zr.

Hf	**O**						
(α)	Sol. soln range, in eq. with oxide	0.66	212.7	—	773–1 323	IIc and IIIb(i)	108
(β)	v. low	0.32	171.2	—	2088–2 403	IIa(ii), p.c.	307

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Hf	Ti		$10^9\tilde{D}$ @				
		1 273 1 373 1 473 1 573 1 673 1 773 1 873			1 973 2 073 2 173 2 273 K		
—	10				50 114 120 125		
—	20				55.2 82 149		
—	30			22.0 33.8 53.6	100		
—	40		8.2	24.8 40.7 78.3	130		
—	50	2.6 5.4	8.6	23.2 49.6 82.4		IIa(i), p.c.	301
—	60	0.8 3.0 6.4	9.7	25.8 49.5 103.0			
—	70	1.1 3.3 7.1	11.0	29.3 54.8 106.0			
—	80	1.4 3.7 7.9	11.5	29.8 57.0 112.0			
—	90	1.6 4.1 8.5	12.7	30.6 55.0 105.0			
Hf	W						
2–10	7.2×10^{-3}	197.6	—	1 823–2 173		IIa(i)	234
Hf	Zr						
	0–100	*See* Figure 13.35		—	1 123–1 773	IIa(i)	235
Hg	Pb						
0–4		0.35	79.5	—	450–470	IIa(i)	46
In	Ni						
0–9	—	0.027[a]	206.4	—	1 173–1 373	IIa(i), p.c.	296

(*a*) *A* estimated from a graph.

In	Pb						
0–1		—	—	2.3×10^{-10}	558	IIa(ii)	46
				3.5×10^{-11}	525		
0–3				3.5×10^{-10}	593		
In	Pd						
20–60	—	*See* Digure 13.36		—	388–446	IIa(i)	245
Ir	W						
3	(α)	3.9×10^4	711.8				
24	(σ)	2.4×10^{-4}	254.6				
50	(ε)	15.0	504.1	—	1 573–2 383	IIa(i)	140
60	(ε)	15.0	504.1				
90	(β)	1.1×10^3	608.8				

(*a*) Arrhenius plots non-linear. *Q* and *A* calculated from measurements at the highest temperatures.

La	Mg						
Sol. soln range in La		0.022	102.2		813–871	IIc	210 and 174
La	U						
Sol. soln range	(γ)	117.0	233.2	—	1 123–1 363	IIc	109
Li	Si						
V. small		2.5×10^{-3}	63.2	—	1 073 and 1 623	IIIb(ii)	110
Li	Sn						
$Li_{1+d}Sn$ $Li_{7+d}Sn_3$ $Li_{5+d}Sn_2$ $Li_{13+d}Sn_5$ $Li_{7+d}Sn_2$ $Li_{22+d}Sn_5$		Extensive graphical data for $\tilde{D}$ as a function of the departure *d* from stoichiometry for all six phases.			688	Electrochem. method	279
Li	W						
n.s., but probably small		5.0	173.8	—	1 363–1 503	IIIb(ii)	111
Li	Zr						
Sol. soln range		0.73	141.1	—	1 048–1 123	IIa(ii)	143

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Mg	Ni						
0–<1		0.44	234.5	—	1 323–1 573	IIa(ii)	112
Mg	Pb						
0.26		—	—	$2.5-3.7\times10^{-10}$	523	IIa(iii)	113
1.0		—	—	6.9×10^{-10}			
2.0		—	—	8.6×10^{-10}	523	IIa(i)	
3.0		—	—	1.1×10^{-9}			
4.1		—	—	$6.4-7.8\times10^{-10}$	523	IIa(iii)	
0.26		—	—	9.4×10^{-10}	543	IIa(iii)	
		—	—	1.2×10^{-10}	493		
1.9		—	—	1.3×10^{-10}	543		
Mg	Pu						
		$\tilde{D}$ at T =	420°C	475°C	534°C		
	0.01	in units 10^{-11}	6.1	25.0	130	IIa(i)	118
	0.56		3.5	11.3	46.3		
	1.12		3.1	9.3	49.7		
	1.7		2.1	13.0	23.5		
Mg	U						
	0.025	—	—	1.2×10^{-11}	400	IIa(i)	118
				3.6×10^{-11}	500		
Mn	Ni						
0–4		7.5	280.9	—	1 373–1 573	IIa(ii)	23
5	—	$\ln A =$	~271 [a]			IIa(i), p.c.	285
10	—	$2.25\times10^{-2}\tilde{Q}$	~262				
15	—	−4.19	~254	—	1 073–1 323		
20	—		~247				
25	—		~241				
		$10^{11}\tilde{D}$	$10^{11}D_{Mn}$	$10^{11}D_{Ni}$			
19.7	—	2.79	4.62	1.40	1 173		
		9.26	10.4	4.83	1 223		
		28.2	32.4	12.2	1 273		
		58.4	66.3	27.5	1 323		
Mn	Ti						
8	(β)	1.10^{-3}	147.4	—	1 103–1 463	IIa(i) and IIIa(ii)	26
		(Very small dep. of $\tilde{D}$ on c in range 2–13%)					
Mo	N						
	Sol. soln range	4.3×10^{-3}	108.9	—	1 573–2 273	IIIb(ii)	199
	Supersat. sol. soln	3×10^{-3}	115.6	—	1 773–2 273	IIIb(ii)	200
Mo	Nb						
~0		1.10^{3}	552.7	$D_{Nb}\sim$	2 073–2 438	IIa(i)	115
50		1.10^{3}	573.6	$3–6\times$			
~100		1.10^{3}	573.6	D_{Mo}			
20		13.5	428.7	—	1 673–2 648	IIa(i)	211
40		3.8	413.2	—			
60		2.1	410.7	—			
80		0.052	345.4	—			
20–80		1.5	399.4	(Average representation of values above)			
Mo	Ni						
0–0.93		3.0	288.5	—	1 423–1 673	IIa(ii)	112
0–9		0.853	269.6	—	1 273–1 573	IIa(ii)	47
Mo	O						
		3×10^{-2}	129.8	—	433	V[a]	58

(a) Values estimated from a graph.

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Mo	Pd						
	61	5.5×10^{-5}	188.4				
	66	4.0×10^{-5}	165.4	$D_{Pd} \approx$ [a] $10–20 \times D_{Mo}$			
	71	5.0×10^{-5}	177.9				
	75	2.4×10^{-4}	200.5	—			
	80	1.6×10^{-3}	218.6	—	1 273–1 873	IIa(i)	175
	85	1.6×10^{-2}	253.3	—			
	90	9.0×10^{-1}	293.1	—			
	95	1.4×10^{-1}	282.6	—			

(*a*) At the original composition in pure Mo/pure Nb couples.

Mo	Ta						
	'Ta rich'	4.68×10^{-5}	251.2	—	2 175–2 573	IIa	190
	'Mo rich'	4.16×10^{-5}	234.5	—			
Mo	Ti						
0		$\sim 2 \times 10^{-2}$	196.8	—			
10		$\sim 2 \times 10^{-2}$	209.3	D_{Ti}/D_{Mo}			
20	(β)	$\sim 1 \times 10^{-2}$	217.7	~ 3 at 1 600° ~ 13 at 820°	1 483–1 873	IIa	190
30		$\sim 10^{-2}$	263.8	—			
40 [a]		$\sim 10^{-2}$	255.4	—			
0–10	(β)	1.3×10^{-4}	138.6	—	1 173–1 573	IIa(ii)	114
Sol. soln range	(α)	3.5×10^{-8}	118.9	—	873–1 073		

(*a*) Results are reported in reference 115 for the whole composition range (0–100%), but for > 40% Mo values vary greatly with type of couple used–incremental or pure metals.

Mo	U						
2		2.2	198.9				
4		9.58	191.8				
6		20.0	221.9				
8		16.0	230.3				
10		237.8	—				
12	(γ)	3.2	218.6	1.123–1.323			
16		0.096	191.3				
20		3.10^{-3}	165.0			IIa(i)	116
24		4.5×10^{-4}	161.2				
26		2.1×10^{-4}	142.4				
				D_*	D_{Mo}		
6.0		—	—	3.4×10^{-9}	5.2×10^{-10}	1 123	
				1.4×10^{-8}	2.1×10^{-9}	1 223	
8.0		—	—	1.6×10^{-8}	5.0×10^{-9}	1 273	
10.0		—	—	3.4×10^{-8}	1.3×10^{-8}	1 323	
Mo	W (wt%)						
	10	4.48	490.7	—			
	20	2.41	481.1	—			
	30	0.64	458.9	—			
	40	0.48	457.6	—			
	50	0.30	450.9	—	2 273–2 773	IIa(i)	119
	60	0.17	441.3	—			
	70	0.14	438.4	—			
	80	0.08	430.0	—			
	90	0.05	422.0	—			
Mo	Zr						
	0–10	1.6	449.2		1 923–2 108	IIa(ii)	
	0–10	—	—	1.3×10^{-11} to 3.7×10^{-11}	2 108	IIa(i)	115
(Mo_2Zr)	$33\frac{1}{3}$	1.10^{-3}	232.8	—	1 093–1 718	IIc	

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
N	Nb						
		6.3×10^{-2}	161.5	—	623–1 873	Combined data, several sources	247
N	Ni						
		3.0×10^{-6}	95.6	—	423–773	IIa(ii), ion implant	310
N	Re						
		1.4×10^{-1}	153.7		1 573–2 173	IIIb(ii)	57
N	Ta						
		5.21×10^{-3}	158.48	—	483–1 673	Combined data, several sources	121
N	Th						
Sol. soln range	(α)	2.1×10^{-3}	94.2	—	1 118–1 763	IIb(i)	122
50–400p.p.m.	(β)	3.2×10^{-3}	91.2	—	1 723–1 988	IIa(ii)	159
N	Ti						
v. low	(α)	0.21	224.0	—	723–973	IIa(i). p.c.	304
Conc. range at diff. temp	(α)	0.012	176.9	—	1 173–1 843	IIIc(i)	123
Sol. soln range	(β)	0.035	141.5	—	1 173–1 843	IIIa(i)	
Composition ranges at diff. temps	(α)	0.2	238.6	—	1 623–1 973	IIc	177
	(δ) (TiN)	20	376.8	—			
N	V						
		1.1×10^{-2}	145.1	—	440–630	Combined data, several sources	247
N	W						
0–300 torr.		2.4×10^{-3}	118.9	—	1 673–2 473	IIIb(ii)	199
1–25 torr.		2.37×10^{-3}	150.3	—	1 273–2 073	IIIb(ii)	207
v. low		4.3	224	—	873–1 073	IIa(ii), p.c.	308
N	Zr						
v. low	(α)	0.56	241.4	—	773–973	IIa(ii), p.c.	305
Comp. range at diff. temp.	(α)	0.3	238.6	—	1 623–2 023	IIc	177
Comp. range at diff. temp.	(α)	0.15	226.5	—	923–1 123	IIIa(i)	178
Sol. soln range	(β)	0.015	128.5	—	1 193–1 913	IIIa(i)	124
Comp. range at diff. temp.	(δ)	0.06	251.2	—	1 623–1 973	IIc	177
N	Zr Hf						
Sol. soln range	(β) 1.8–2.2	0.03	140.7	—	1 173–1 873	IIIa(i)	125
N	Zr Sn (wt%)						
Sol. soln range	(β) 1.8	0.011	131.5	—	1 438–1 913		
	2.6	0.0014	129.4	—	1 373–1 803	IIIa(i)	126
	5.0	0.011	123.1	—	1 373–1 763		
Nb	O						
		5.86×10^{-3}	109.65	—	296–1 823	Combined data, several sources	121

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Nb	Ta						
	10	1.1×10^{-2}	343.3	—	2 274–2 653	IIa(i)	246
	20	1.34×10^{-2}	351.7	—			
	25	1.0×10^{-2}	343.3	—			
	35	9.3×10^{-2}	347.5	—			
	40	1.0×10^{-2}	351.7	—			
	45	1.56×10^{-2}	360.1	—			
	55	1.25×10^{-2}	364.3	—			
	60	2.0×10^{-2}	373.6	—			
	65	3.16×10^{-2}	385.2	—			
	70	4.4×10^{-2}	393–6	—			
	75	5.6×10^{-2}	397–7	—			
	90	1.24×10^{-1}	414.5	—			
Nb	Ti	[a]					
	0	2.5×10^{-3}	293.1	$D_{Ti} \sim 2 \times D_{Nb}$	1 273–1 863	*IIa(i)*	115
	20	2.5×10^{-3}	263.8				
	40	3.2×10^{-3}	238.6				
	60	3.8×10^{-3}	209.3				
	80	3.8×10^{-3}	184.2				
	100	3.8×10^{-3}	167.5				

(*a*) Values taken from smoothed plots of *A* and *Q* against composition.

Nb	U(γ)	[a]					
	2	2.8×10^{7}	623.4				
	12	2.3×10^{7}	603.7	—	1 773–1 923	IIa(i)	127
	18	9.6×10^{6}	586.2				
	22	0.091	307.7	—	1 673–1 873		
	28	0.113	305.2	—			
	38	0.149	304.8	—	1 573–1 773		
	46	0.064	284.7	—	1 423–1 673		
	54	0.45	292.7	—	1 423–1 623		
	62	0.84	286.8	—	1 348–1 573		
	68	1.94	291.8				
	74	0.82	252.9	—	1 223–1 448		
	78	1.16	252.5				
	82	1.19×10^{-4}	139.8	—	1 165–1 398		
	93	1.63×10^{-4}	126.4	—	966–1 298		
	97	2.31×10^{-4}	125.2				
	97	D_U— 3.82×10^{-3}	124.8	—	966–1 298		
		D_{Nb}— 7.1×10^{-3}	1 645				
	4	—	—	$D_{Nb} \sim 30 \times D_U$			
	10–100	—	—	$D_U > D_{Nb}$			

(*a*) This is a representative selection from a larger table of values in reference 127.

Nb	V						
	0	1.6×10^{-2}	910.3	$D_V \sim 3–5 \times D_{Nb}$	1 678–2 023	IIa(i)	150
	20	1.95×10^{-2}	343.3				
	40	2.3×10^{-2}	293.1				
	60	2.8×10^{-2}	268.0				
	80	3.3×10^{-2}	263.8				
	100	3.8×10^{-2}	263.8				
Nb	W (wt%)						
	10	81.45	439.6	—	2 273–2 673	IIa(i)	119
	20	22.2	418.7	—			
	30	1.97	376.4	—			
	40	1.4×10^{-2}	280.1	—			
	50	7.4×10^{-3}	272.1	—			
	60	3×10^{-3}	252.0	—			
	70	1.8×10^{-3}	289.3	—			
	80	1.0×10^{-3}	236.1	—			
	90	6.0×10^{-4}	228.2	—			

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Nb	Zr						
5		—	217.7	—			
30		—	247.0	—	1 173–1 873	IIa	179
95		—	332.9	—			
0		$\sim 10^{-2}$	~196.8	—			
20		$\sim 4 \times 10^{-2}$	~209.3	—			
40		$\sim 10^{-1}$	~255.4	—			
60	[a]	$\sim 3 \times 10^{-1}$	301.4	—	1 718–1 963	IIa(i)	115
80		~2	~349.5	—			
100		~10	~389.4	—			
—	0–5	1.2	349.26	—	2 070–2 370	IIIa(ii), p.c.	269

(*a*) Values taken from smoothed plots of *A* and *Q* against composition.

Ni	O						
	[a]	7.9×10^4	309.4	(s.c.)	1 073–1 473	Internal oxidation method	201
	[b]	9.5×10^4	311.5	(p.c.	1 173–1 573		
		12.1	241	—	623–1 273	IIIb(ii), p.c.	202

[a] Ni + 0.58%Si. s.c.
[b] Ni + 0.48%Si. p.c.

Ni	Pb						
0–3		~0.66	105.9	—	558–593	II	46

Ni	Pb		$\tilde{D} \times 10^{11}$				
		859°C	*950°C*	*1019°C*	*1150°C*		
10		0.68	1.30	1.79	18.6		
20		1.03	2.01	3.37	30.0		
30		1.52	3.54	7.39	70.4		
40		1.72	5.37	11.7	98.2		
50		1.97	6.61	16.1	1.58	IIa(i)	144
60		1.40	5.42	15.6	131		
70		0.84	3.06	11.3	104		
80		0.56	1.90	5.58	58.7		
90		0.50	1.25	2.30	35.0		

Ni	Pt						
0–14.9		7.9×10^{-4}	180.5	—	1 316–1 674	IIa(ii)	28
	0–100		Figure 13.32		1 223–1 573	IIa(i)	218

Ni	Si						
	0–<1	1.5	258.3	—	1 393–1 573	IIa(ii)	112
wt.%	2.3	0.3[a]	240	—	1 373–1 523	IIa(i), p.c.	311

Ni	Sn						
—	0	2.5	260				
—	1	2.5	259				
—	2	2.3	257				
—	3	2.3	255				
—	4	1.9	251	—	1 223–1 473		
—	5	2.5	253				
—	6	2.4	251				
—	7	2.3	250			IIa(i), p.c.	261
		$10^{14} D_{Ni}$	$10^{14} D_{Sn}$				
—	0.8	1.9	3.4				
—	2.2	2.2	3.7				
—	2.2	1.8	4.2	—	1 373		
—	4.5	3.0	6.0				

Ni	Ti						
	0–0.9	0.86	257.1	—	1 373–1 573	IIa(ii)	23

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Ni	Ta						
Ta_2Ni		2.6×10^{-3}	230.7	—	1 423–1 573	II	236
TaNi		2.1	306.9	—			
$TaNi_2$		0.1	250.4	—			
$TaNi_3$		1.7×10^{-5}	133.6	—			
$TaNi_8$		0.9×10^{-2}	334.1	—			
Ni	U						
0-sol. limit	(γ)	2500	192.6	—	1 123–1 273	IIc	54
Ni	V						
	0–16.5	0.287	247.9	—	1 373–1 573	IIa(ii)	47
Ni	W						
	0–1.5	11.1	321.5	—	1 423–1 563	IIa(ii)	23
	0–5	0.86	294.8	—	1 373–1 573	IIa(ii)	47
	1	2.24	303.0	—	1 273–1 589	IIa(i)	180
	2	2.16	303.5	—			
	3	2.11	303.8	—			
	4	2.07	304.2	—			
	5	2.04	304.5	—			
	6	2.01	304.8	—			
	7	1.98	305.2	—			
	8	1.95	305.6	—			
	9	1.94	805.9	—			
	10	1.92	306.3	—			
	11	1.90	306.7	—			
	12	1.89	367.2	—			
Ni	Zn						
	5–95	$1.05 \times 10^3 \times \exp(-0.142 C_{Ni})$	180.0	—	873–1 273	IIa(i)	181
		A_{Ni} 8.3×10^{-2}	Q_{Ni} 182.1				
		A_{Zn} 0.176	Q_{Zn} 203.1				
δ		7.1×10^{-2}	85.0	—	483–873	II	237
γ'		1.2×10^{-1}	90.9	—			
γ''		3.0×10^{-2}	96.7 (a)	—			
—	5	$\ln A = 2.4 \times 10^{-2} \bar{Q} - 5.6$	~265	—	1 073–1 323	IIIa(i)	286
—	10		~252				
—	15		~242				
—	20		~236				
—	25		~219				
—	30		~208				
O	Pt						
Sol. soln range		9.3	326.6	—	1 708–1 777	Ic	204
O	Ta						
0–1.13		1.05×10^{-2}	110.43	—	298–1 673	Combined data, several sources	121
O	Th						
25–220 p.p.m.	(β)	1.3×10^{-3}	46.1	—	1 713–1 973	IIa(ii)	159
	(α)	1.3×10^{2}	209.2		1 273–1 473	IIa(ii)	248
O	Ti						
α-sol. soln		0.45	201	—	573–1 223	IIIa(i), p.c.	130
β-sol. soln		0.14	138.2	—	1 023–1 623	IIIa(i) and IIa(ii)	123 and 287

(a) Values estimated from a graph.

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
O	**V**						
		2.46×10^{-2}	123.5	—	333–2098	Various	247
O	**Zr**						
Sol. soln range	(α)	1.32	201.8	—	563–1 773	Various	131
	(α)	0.0661	184.2	—	563–923		
		16.5	229.0	—	923–1 773		
Sol. soln range	(β)	0.977	171.7	—	1 322–1 473	III	183
	(β)	2.63×10^{-2}	118.1	—	1 273–1 573	IIa(ii) and IIc	306
Sol. soln range	(α) (Zircalloy)	0.196	171.7	—	1 273–1 773	IIIc(i)	132
Sol. soln range	(β) (Zircalloy)	0.0453	118.1	—	1 273–1 773	IIIa(i)	132

(a) Reference 131 reviews all published data. Quoted *A*'s and *Q*'s are 'best mean values'. Data slightly better represented by two Arrhenius expressions, above and below 650°C.

Pb	Sn						
	0–2	4.0	99.6	—	518–573	IIa(ii)	10
	Sol. soln range		100.5	$\tilde{D}$ increases with conc. of Sn	443 and 454	IIa(i)	135
—	0	—	—	3×10^{-11}	523	IIa(i), p.c.	284
—	5	—	—	9.5×10^{-11}			
—	10	—	—	2×10^{-10}			
Pb	Tl						
	0–2	0.025	81.2	—	493–558	IIa(ii)	29
	0.53	1.03	103.0	Almost independent of conc.	533–588	IIa(i)	113
Pd	Pt						
0	—	$\sim 4 \times 10^{-3}$	~54	—	1 335–1 676	IIa(i), p.c.	290
10	—	$\sim 4 \times 10^{-3}$	~54				
20	—	$\sim 5 \times 10^{-3}$	~54.5				
30	—	$\sim 5 \times 10^{-3}$	~55				
40	—	$\sim 6 \times 10^{-3}$	~56				
50	— [a]	$\sim 8 \times 10^{-3}$	~57				
60	—	$\sim 1.0 \times 10^{-2}$	~58				
70	—	$\sim 1.3 \times 10^{-2}$	~59				
80	—	$\sim 2.5 \times 10^{-2}$	~61				
90	—	$\sim 5.0 \times 10^{-2}$	~64				
100	—	$\sim 9.5 \times 10^{-2}$	~67				

(*a*) Rough values estimated from graphs.

Pd	Ti						
	(β)	1.26×10^{-3}	131.9	—	973–1 273	IIa(i)	238
	(γ)	1.6×10^{-8}	44.8	—	973–1 173		
	(δ)	3.6×10^{-4}	129.4	—			
	(ε)	1.6×10^{-6}	84.2	—			
	(η)	6.4×10^{-4}	745.3	—			
				$D_{Ti} = 3.54 \times 10^{-9}$	1 173		
				$D_{Pd} = 1.32 \times 10^{-9}$	1 173		
				D_{Tl}/D_{Pd}	1073		
Pt	W						
2	(β)	3.1×10^{2}	582.0	—	1 573–2 016	IIa(i)	140
50	(γ)[a]	4.7×10^{-3}	350.0				
55		3.3×10^{-3}	343.7				
65	(ε)[a]	4.4×10^{-2}	385.2	—	1 746–2 016		
77	(α)	1.8×10^{-2}	326.6	—	1 573–2 016		
80		1.2×10^{-2}	315.7				
85		1.3×10^{-2}	310.7		1 573–1 973		

(*a*) The γ and ε are two new phases observed during the diffusion experiments and not previously reported.
b Arrhenius plots not always linear. *Q* and *A* derived from measurements at higher temperatures.

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\,mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Pu	Ti						
2	(β)	9.4×10^{-4}	123.9	—	1 173–1 373	IIa(ii)	217
15	(β)	2.3×10^{-3}	127.7	—			
Pu	U						
1.75	(α)	0.14×10^{-7}	56.1	Probably a significant contribution to $\tilde{D}$ from g.b. diffusion	683–813	IIa(i)	134
3.50		0.15×10^{-7}	57.4				
5.25		0.18×10^{-7}	59.0				
7.0		0.28×10^{-7}	63.6				
8.75		0.44×10^{-7}	68.2				
10.50		0.88×10^{-7}	74.9				
12.25		1.18×10^{-7}	78.7				
14.0		2.0×10^{-7}	83.7				
15.75		2.57×10^{-7}	86.2				
Pu	Zr						
20	($\varepsilon\beta$)	7×10^{-1}	184.2	—	1 023–1 173	IIa(i)	189
30		1×10^{-2}	144.4	—	973–1 123		
40		1.5×10^{-3}	119.3	—			
50		2.5×10^{-4}	98.4	—	973–1 143		
60		9×10^{-5}	77.5	—	973–1 143		
(δ)	4.2–11.4	5.89×10^{-6}	83.7	—	624–748	IIa	188
0.115	(α)	0.1	226.1	—	973–1 073	IIa(ii)	192
1.15		11.1	272.1	—			
		A_{Zr}	Q_{Zr}	A_{Pu}	Q_{Pu}		
20	($\varepsilon\beta$)	8×10^{-1}	188.4	6×10^{-1}	184.2	Same T range as for $\tilde{D}$	189
30		7.5	205.2	4×10^{-1}	175.8		
40		2×10^{-1}	167.5	1×10^{-3}	113.0		
50		1.5×10^{-4}	121.4	3×10^{-2}	117.2		
Rh	W						
3	(α)	1.3×10^{-6}	242.8	—	1 573–2 073	IIa(i)	140
60	(ε)	1.5×10^{-6}	174.6				
70		3.1×10^{-6}	181.7				
90	(β)	2.5×10^{-6}	174.2				
Ru	W		(a)				
5	(α)	5.5×10^{-3}	391.5	—	1 573–2 298		
39	(σ)	1.2×10^{-5}	255.4	—	2 058–2 298		
70	(β)	1.8×10^{-5}	207.2	—	1 573–2 298		
90		1.0×10^{-5}	239.5				

(*a*) Arrhenius plots not always linear. *Q* and *A* derived from measurements at highest temperatures.

S	Ni						
~0.01		2.3×10^{6}	376.8	—	1 273–1 473	IIIa(ii)	142
Si	U						
Sol. soln range	(γ)	20	188.4	—	1 123–1 323	IIc	54
Sn	Ti						
1.0	(β)	8.4×10^{-7}	64.1	Increases linearly with C	1 273–1 523	IIa(i)	26
8.0		2.7×10^{-4}	124.8		1 363–1 523		
2.0	(β)	—	—	$D_{Sn} = 9.18 \times 10^{-9}$, $D_{Ti} = 2.65 \times 10^{-9}$	1 523		
Sn	Zr						
Sol. soln range	(α)	3.10^{-4}	92.1	—	873–1 123	IIa(ii)	136
0–3.9	(β)	6.9×10^{-4}	150.7	—	1 373–1 573	IIa(ii)	
0–5	—	0.07	212	—	1 605–1 970	IIIa(ii), p.c.	271
Sr	U						
Sol. soln	(γ)	2.38×10^{-3}	196.8	—	1 073–1 273	IIc	109

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
Ta	W						
	'Ta rich'	1.78	498.2	—	2 373–2 773	IIa	190
	'W rich'	4.16×10^{-2}	418.7	—			
—	20–80	1.0	546.4				
30	70	$A_{Ta}=1.8$ $A_W=0.17$	$Q_{Ta}=553.9$ $Q_W=510.8$	—	1 573–2 373	IIa(ii), p.c.	259
Ti	U						
10.0		11.10^{-3}	153.2				
20.0		1.4×10^{-3}	138.2				
30.0		1.6×10^{-3}	145.7				
40.0		4.0×10^{-3}	160.8				
50.0		9.5×10^{-3}	175.8				
60.0	(γ)	2.6×10^{-3}	165.0	—	1 223–1 348		
70.0		2.6×10^{-3}	165.0				
80		2.2×10^{-3}	157.0				
90.0		1.1×10^{-3}	141.5			IIa(i)	137
95.0		0.46×10^{-3}	126.4				
				D_{Ti} D_U			
165.5		—		5.8×10^{-9} 2.2×10^{-8}	1 348		
				1.2×10^{-9} 4.7×10^{-8}	1 223		
18.0		—		2.9×10^{-9} 9.5×10^{-9}	1 273		
				4.1×10^{-9} 1.6×10^{-8}	1 323		
16.5–18		$Q_U=161.2$	$Q_{Ti}=167.5$				
Ti	V						
(α)	Sol. soln range	—	—	3.91×10^{-15}	873	IIa(ii)	114
				4.7×10^{-15}	973		
(β)	0–10	1.25×10^{-2}	173.3	—	1 173–1 573	IIa(i)	
(β)	2.0	6.0×10^{-3}	165.8	Dep. on c in range 2–12% v. slight	1 173–1 523	IIa(i)	26
(β)	3.5	—	—	$D_{Ti}=1.31 \times 10^{-9}$ $D_V=14.9 \times 10^{-9}$	1 523		
10		8.3×10^{-4}	197.6	—			
20		1.5×10^{-3}	199.3	—			
30		4.4×10^{-3}	203.9	—			
40		1.3×10^{-2}	206.8	—			
50		2.4×10^{-2}	203.5	—	923–1 323	IIa(i)	240
60		1.1×10^{-2}	186.2	—			
70		8.1×10^{-4}	153.2	—			
80		4.1×10^{-4}	139.8	—			
90		1.6×10^{-4}	123.9	—			
—	20	1.6×10^{2}	191.3				
—	40	4.8×10^{-2}	212.7	—	1 173–1 573		289
—	60	0.8	261.7				
—	80	8.2	295.2				
Ti	Zr						
0–4	—	2.69	261	—	1 700–1 953	IIIa(ii), p.c.	271
(α)	0–10	1.7×10^{-12}	49.4	—	873–1 073	IIa(ii)	114
(β)	0–10	1.8×10^{-2}	167.9	—	1 173–1 573	IIa(ii)	114
10		1.4×10^{-2}	164.5	—	1 103–1 323		
25		3.3×10^{-3}	146.5	1 103–1 323			
		5×10^{-7}	65.7	—	923–1 103		
40		2.7×10^{-3}	142.8	—	1 103–1 323		
		1.2×10^{-6}	71.6	—	923–1 103		
50		2.4×10^{-3}	140.7	—	1 103–1 323		
		1.7×10^{-6}	74.1	—	923–1 103		
65		1.6×10^{-3}	136.5	—	1 103–1 323	IIa(i)	239
		2.0×10^{-6}	18.0	75.4	—	923–1 103	
80		1.5×10^{-3}	134.8	—	—	1 103–1 323	
		2.2×10^{-6}	75.4	—	923–1 103		
90		1.3×10^{-3}	131.9	—	1 103–1 323		
50.5				$D_{Zr}=5.1 \times 10^{-10}$ $D_{Ti}=3.2 \times 10^{-10}$	1 073		

Table 13.4 CHEMICAL DIFFUSION COEFFICIENT MEASUREMENTS—*continued*

Element 1 At.%	*Element2* At.%	*A* $cm^2 s^{-1}$	*Q* $kJ\ mol^{-1}$	*D* $cm^2 s^{-1}$	*Temp. range* K	*Method*	*Ref.*
U	W						
'low'		1.8×10^{-2}	389.4	—	2 243–3 003	IIIb	241
U	Xe						
(β)	$0–10^{-6}$	9×10^{-7}	96.3	—	973–1 323		
(γ)	$0–10^{-6}$	10^{8}	410.3	—	1 083–1 333	IIIb(ii)	149
U	Zr						
(γ)	10	9.5×10^{-4}	134.0	–	1 223–1 348	IIa(i)	138
	20	1.3×10^{-4}	119.7				
	30	0.35×10^{-4}	110.1				
	40	0.4×10^{-4}	114.7				
	50	0.8×10^{-4}	124.3				
	60	0.63×10^{-4}	124.3				
	70	0.55×10^{-4}	124.3				
	80	3.2×10^{-4}	143.6				
	90	78×10^{-4}	171.7				
	95	870×10^{-4}	196.8				
	10–95			D_U and D_{Zr} Figures 13.33 and 13.34	1 123–1 313	IIa(i)	139

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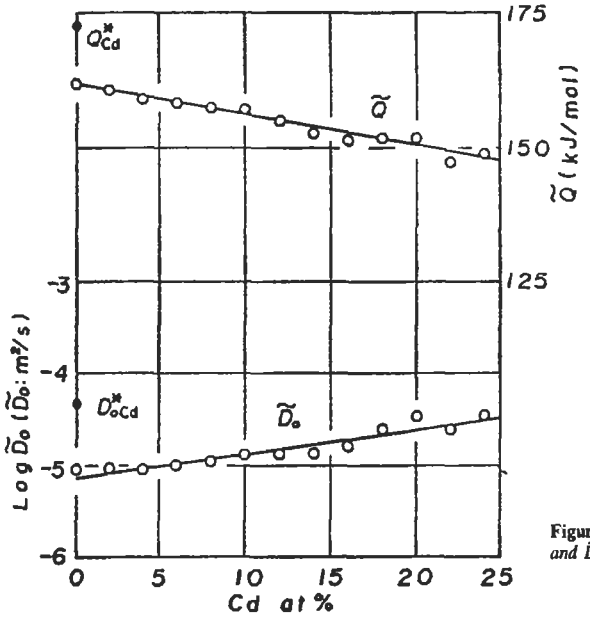


Figure 13.9 *The concentration dependences of* $\tilde{Q}$ *and* $\tilde{D}$ *in* Ag-Cd *alloys*[291]

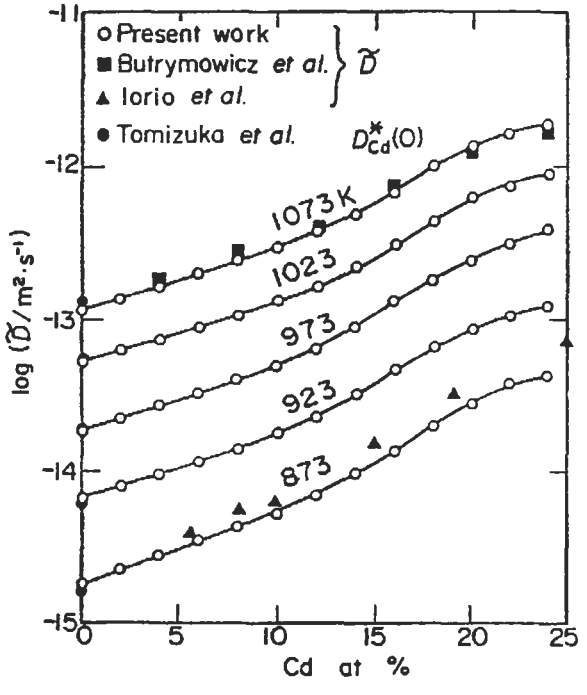


Figure 13.10 *Concentration dependence of the interdiffusion coefficients,* $\tilde{D}$*, at five temperatures between* 873 *and* 1073 K *determined by use of* Ag-25Cd *diffusion couples*[291]

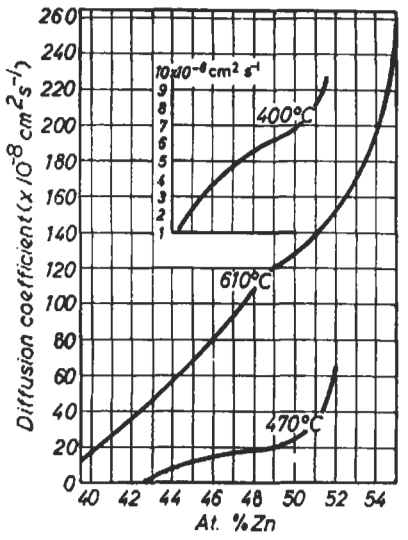


Figure 13.11 *Chemical diffusion coefficients in* AgZn *alloys*[11] *Table 13.4*

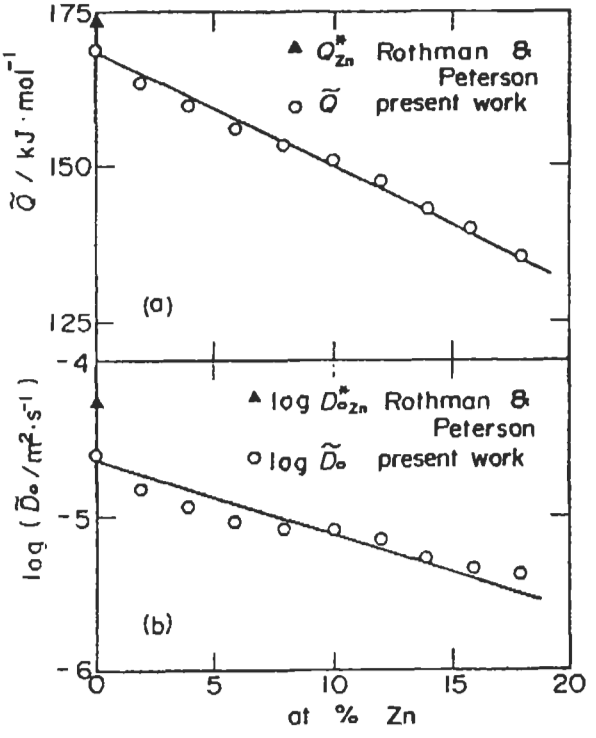


Figure 13.12 *Concentration dependence of* $\tilde{Q}$ *(a) and* log $\tilde{D}_o$ *(b) in* Ag-Zn α *phase*[312]

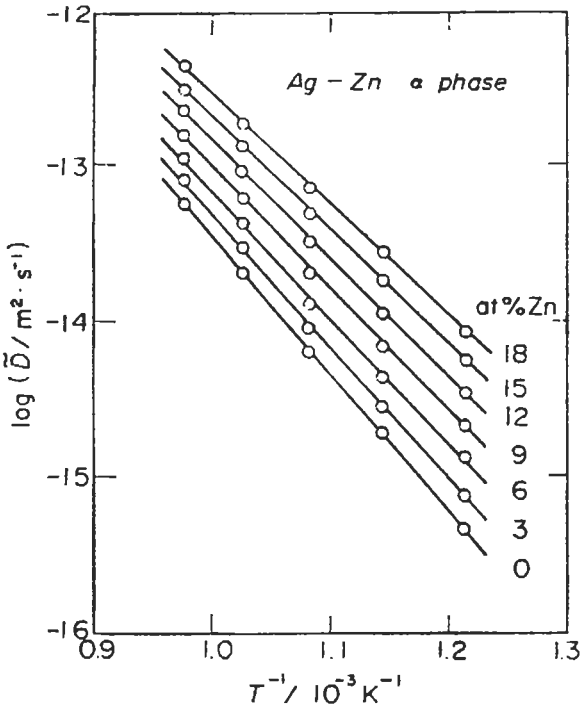


Figure 13.13 *Temperature dependence of the interdiffusion coefficients in* Ag-Zn α *phase*[512]

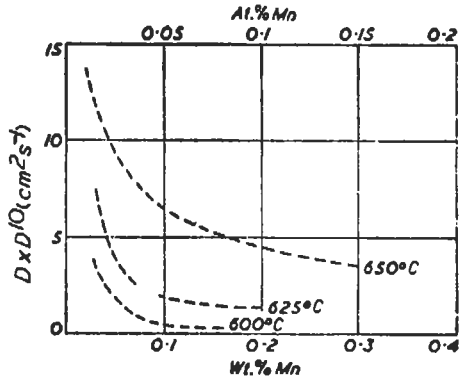


Figure 13.14 *Chemical diffusion in* AlMn *alloys*[21]

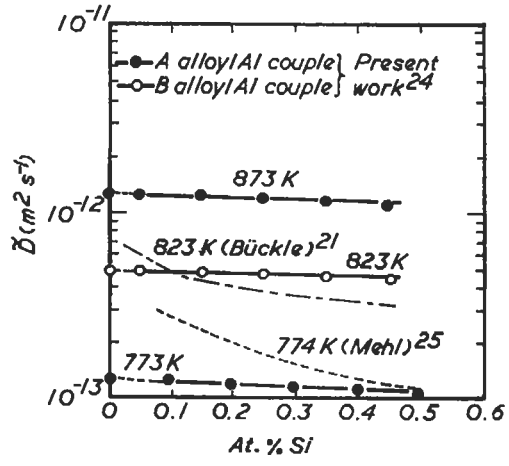


Figure 13.15 *Chemical diffusion in* AlSi *alloys*[21,25]

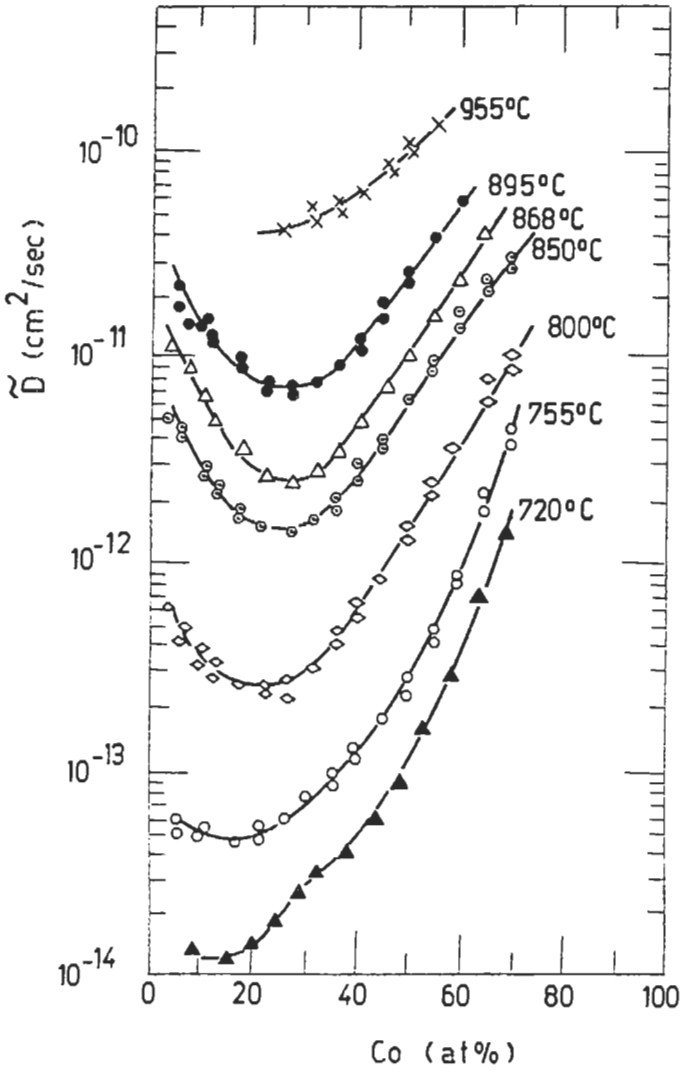


Figure 13.16a *Interdiffusion in b.c.c.* FeCo *alloys*[318]

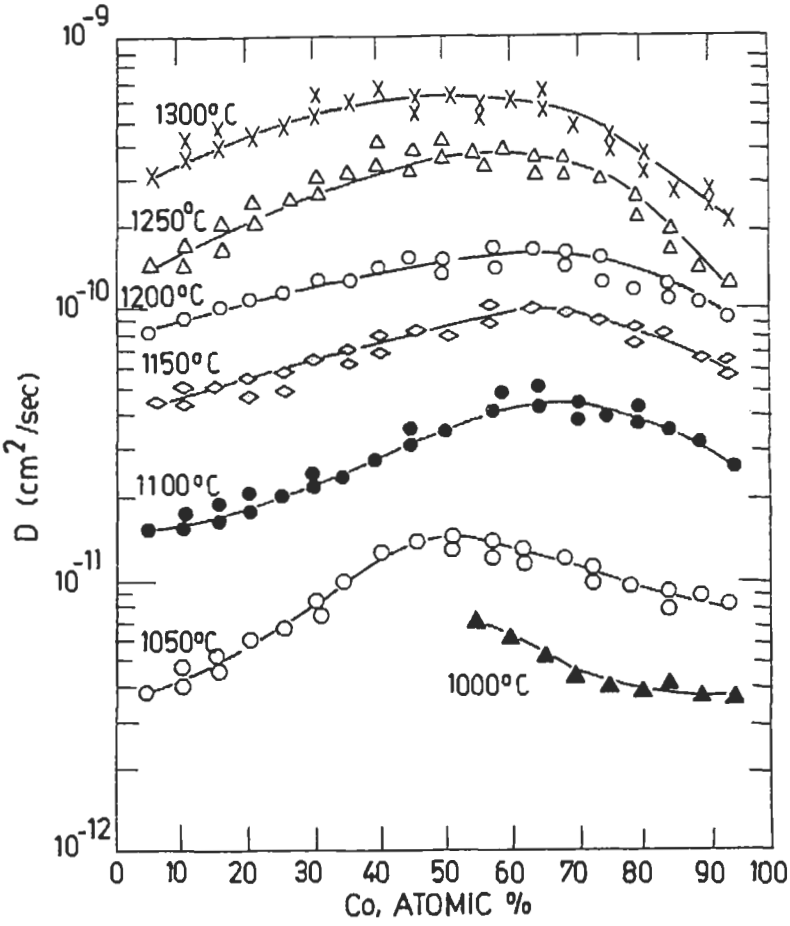


Figure 13.6b *Interdiffusion in f.c.c.* FeCo *alloys*[318]

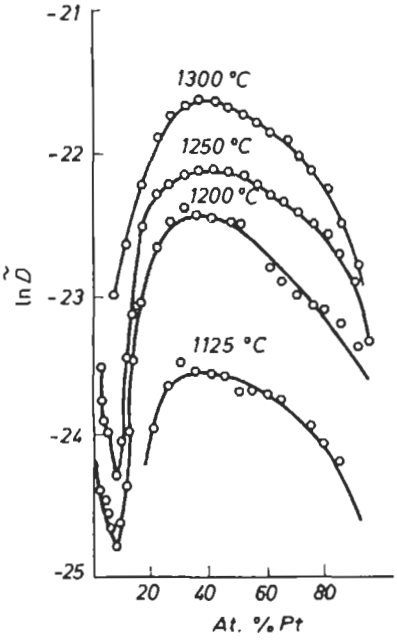


Figure 13.17 *Interdiffusion in* Co-Pt[218]

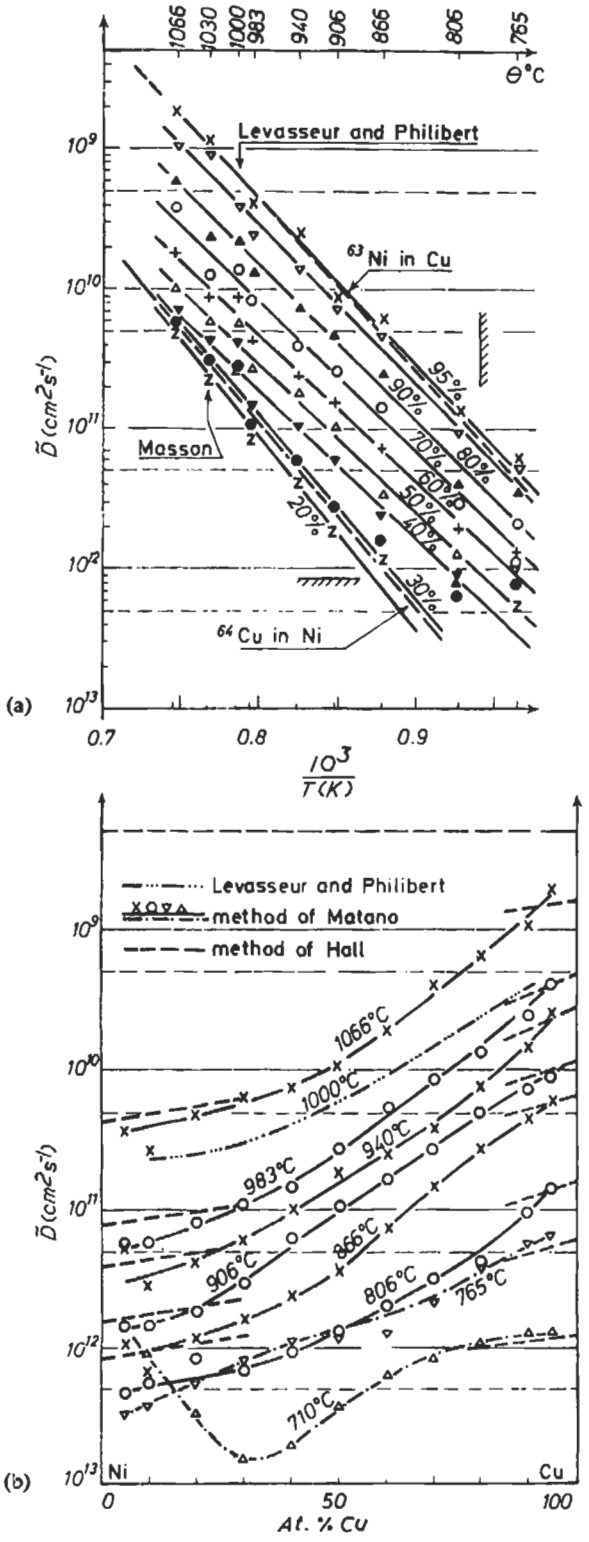


Figure 13.18 *Interdiffusion in* Cu-Ni[55] *(a) as function of* 1/T; *(b) As a function of composition*

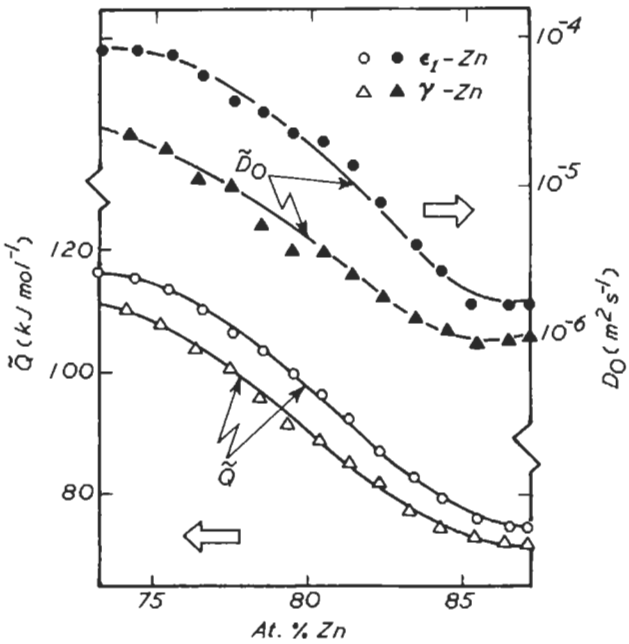


Figure 13.19 *Chemical diffusion* AgZn *alloys*[221]

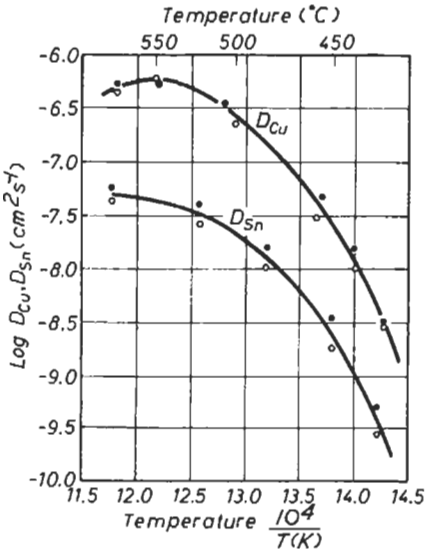


Figure 20 *Partial diffusion coefficients for* Cu *and* Sn *in δ-phase* CuSn *alloys*[60]

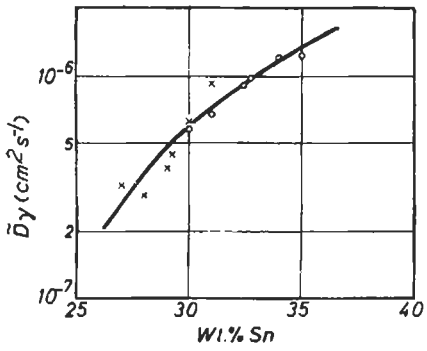


Figure 13.21 *Chemical diffusion coefficients for γ-phase of* Cu-Sn *systems at* 706.5°C[60]

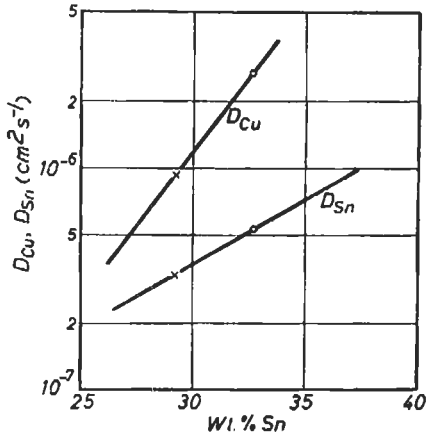


Figure 13.22 *Partial diffusion coefficients for* Cu *and* Sn *in* γ CuSn *alloys at* 706.5°C

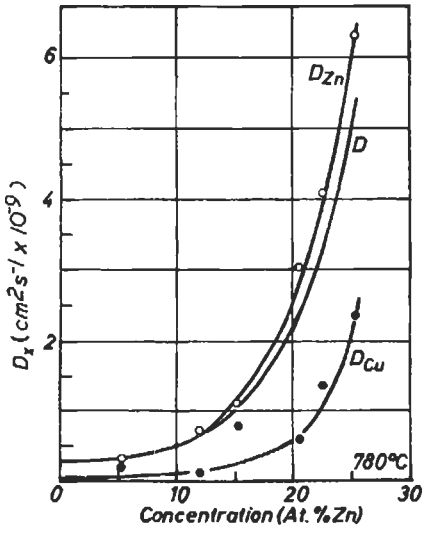


Figure 13.23 *Chemical and partial diffusion coefficients in* α-Cu-Zn *system at* 780°C[61]

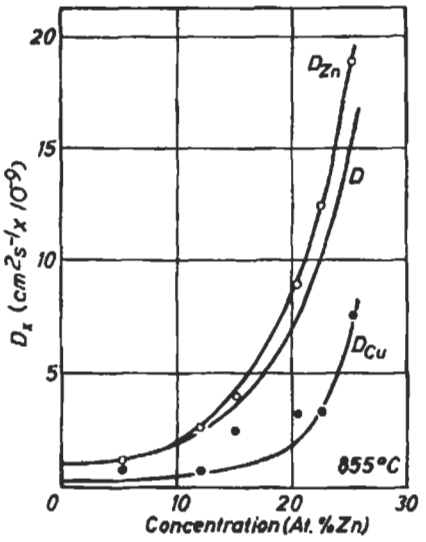


Figure 13.24 *Chemical and partial diffusion coefficients in* α-Cu-Zn *systems at* 855°C[61]

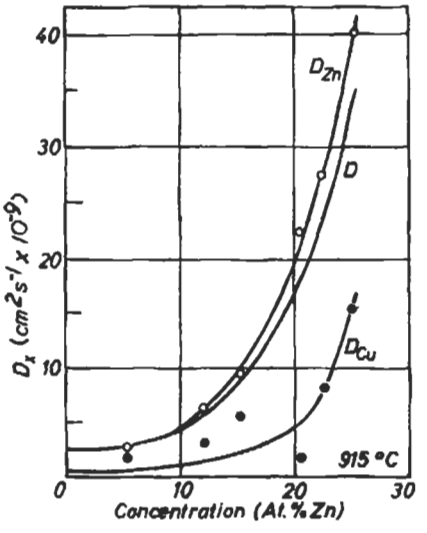


Figure 13.25 *Chemical and partial diffusion coefficients in* α-Cu-Zn *system at* 915°C[61]

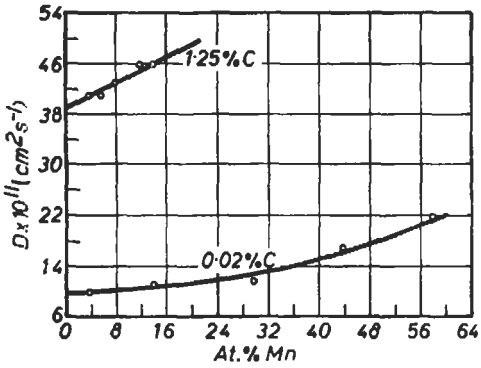


Figure 13.26 *Chemical diffusion coefficients in* γ-Fe Mn *alloys with* 0.02 *and* 1.25 wt% C. *Temperatur* 1 200°C[67]

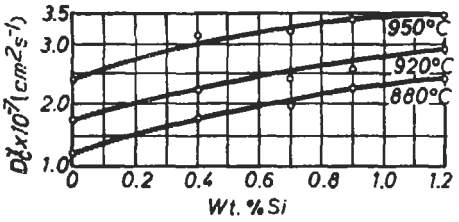


Figure 13.27 *Effect of* Si *content on chemical diffusion of* C *in* γFe[145]

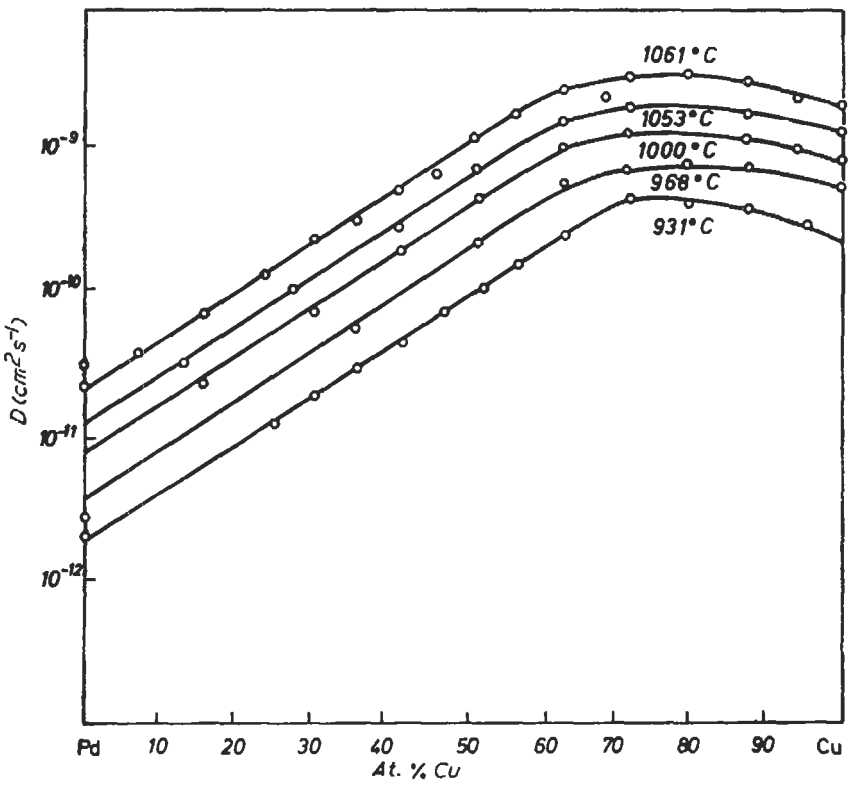


Figure 13.28 *Interdiffusion in the* Cu-Pd *system*[160]

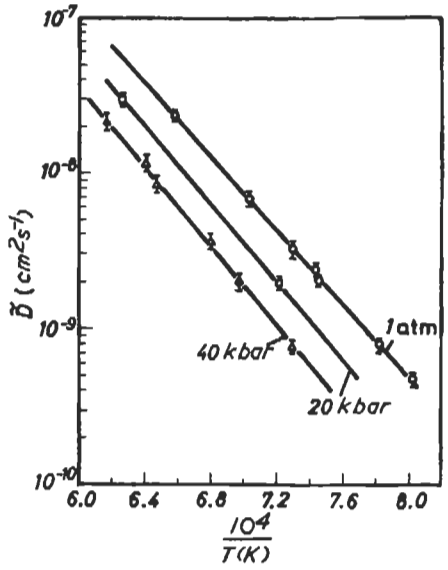


Figure 13.29 *Chemical diffusion in* α-Fe V 10% *alloy at* 1, 20 *and* 24 kbar *pressure*

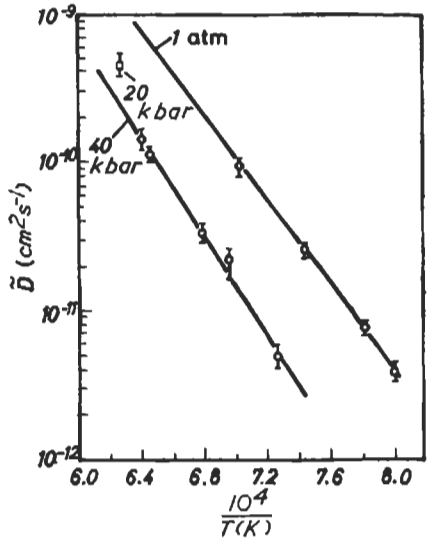


Figure 13.30 *Chemical diffusion in* γ Fe V 0.7% *alloy at* 1, 20 *and* 40 kbar pressure[78]

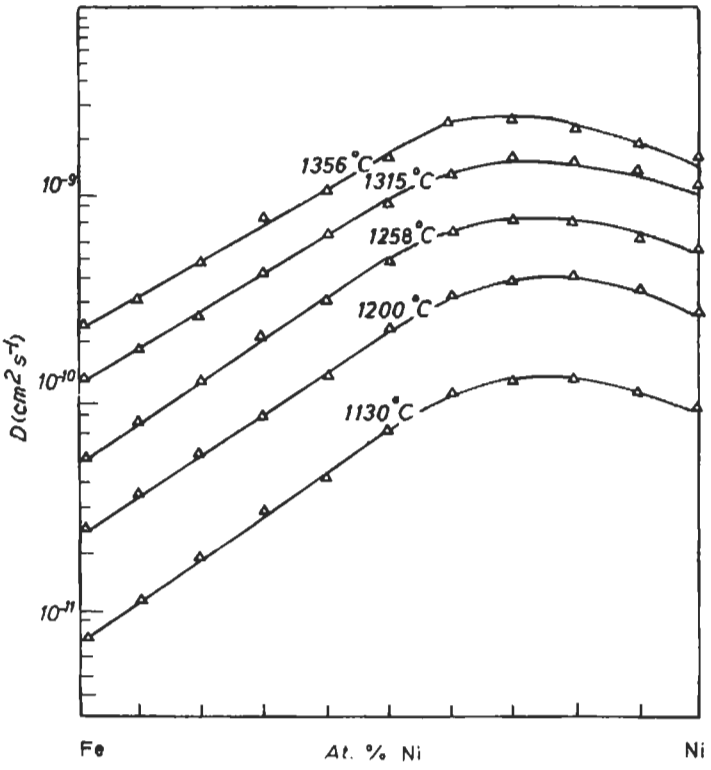


Figure 13.31 *Chemical diffusion coefficients in the* Fe-Ni *system*[160]

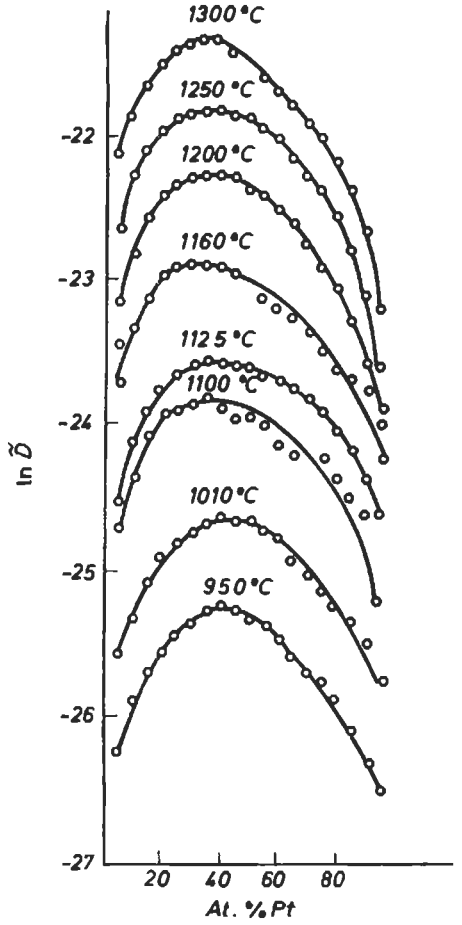


Figure 13.32 *Chemical diffusion coefficients in the* Ni-Pt *system*[218]

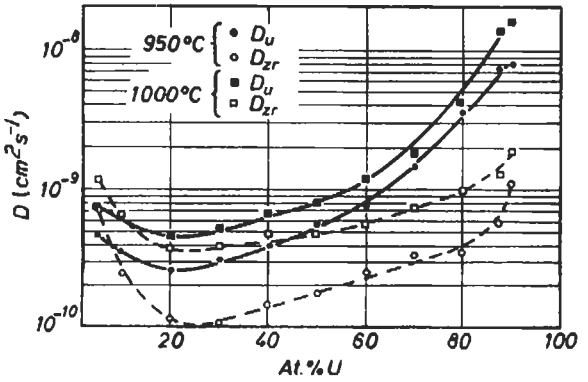


Figure 13.33 *Partial diffusion coefficients* D_U *and* D_{Zr} *in* γ U-Zr *alloys*[139]

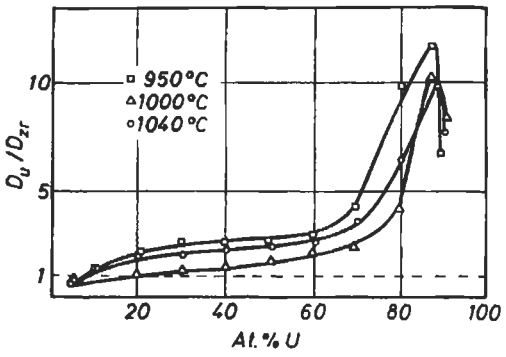


Figure 13.34 *Ratio of partial diffusion coefficients in γ* U-Zr *alloys*[139]

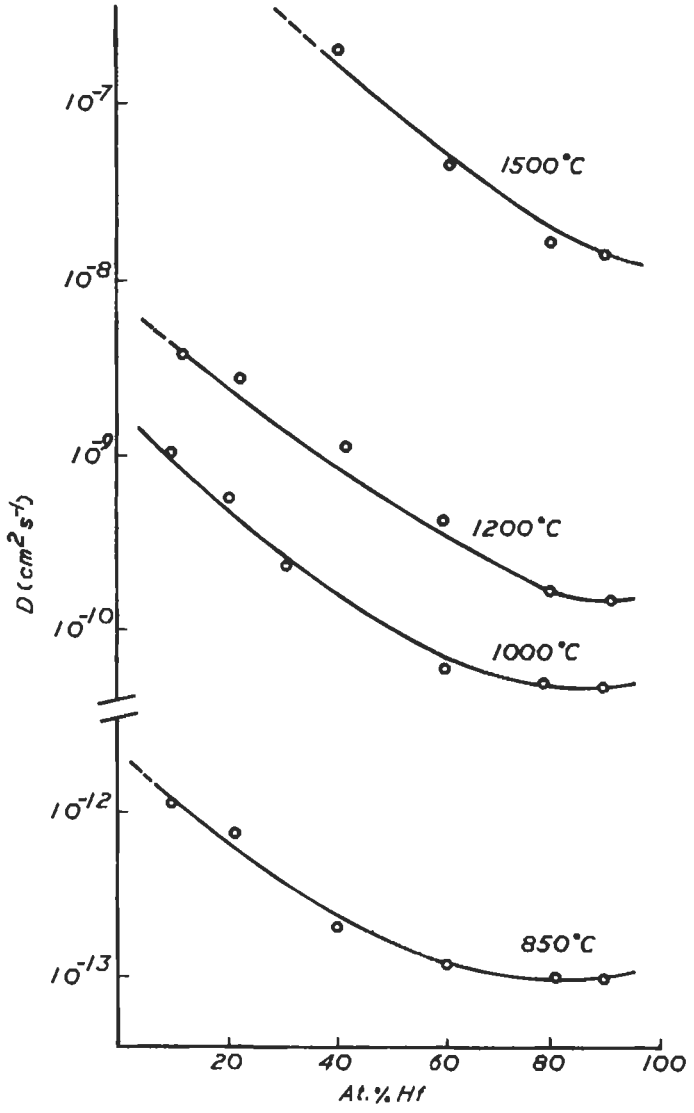


Figure 13.35a *Chemical diffusion in* Hf-Zr *alloys*

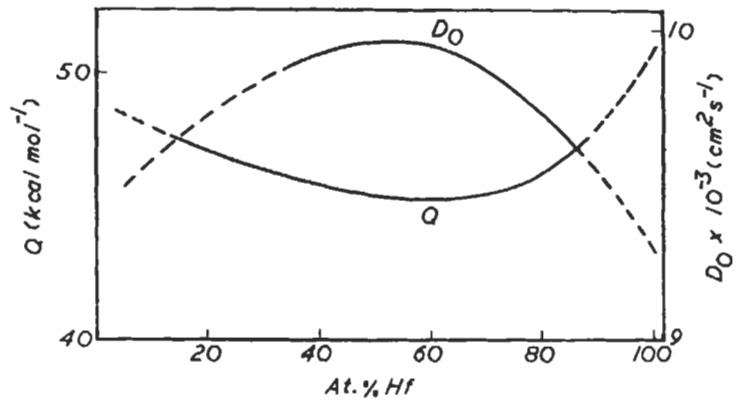


Figure 13.35b *A and Q for chemical diffusion in* Hf-Zr *alloys*[235]

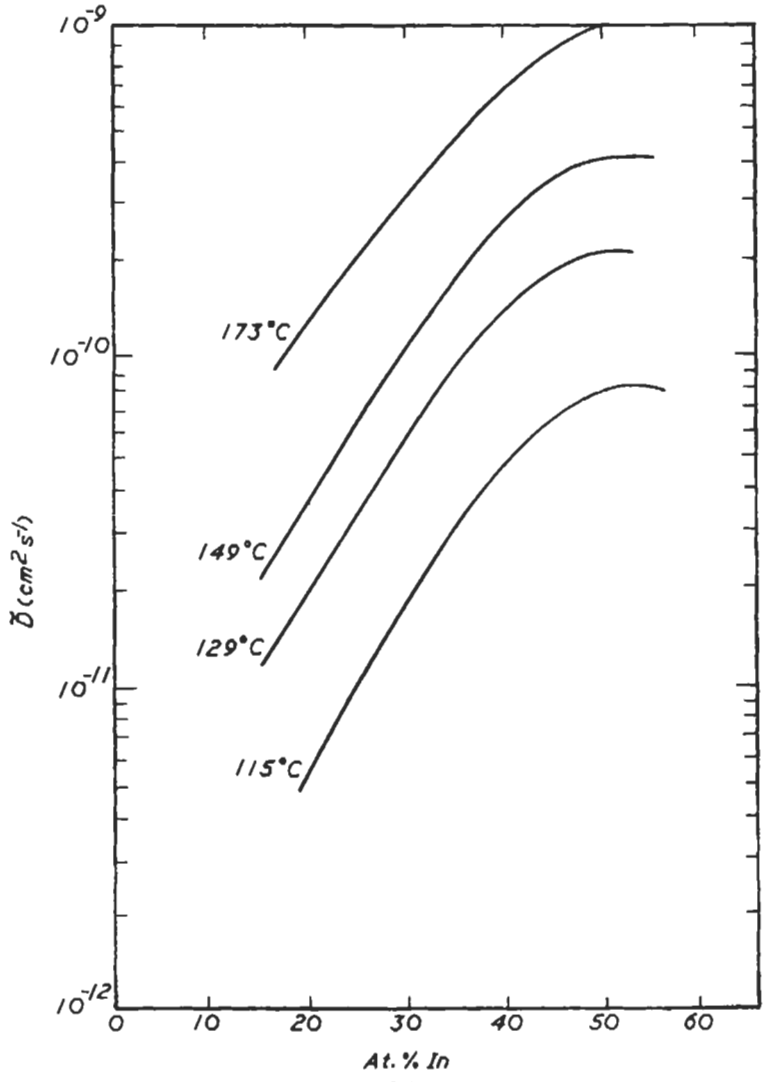


Figure 13.36 *Chemical diffuston in* In-Pb *alloys*[245]

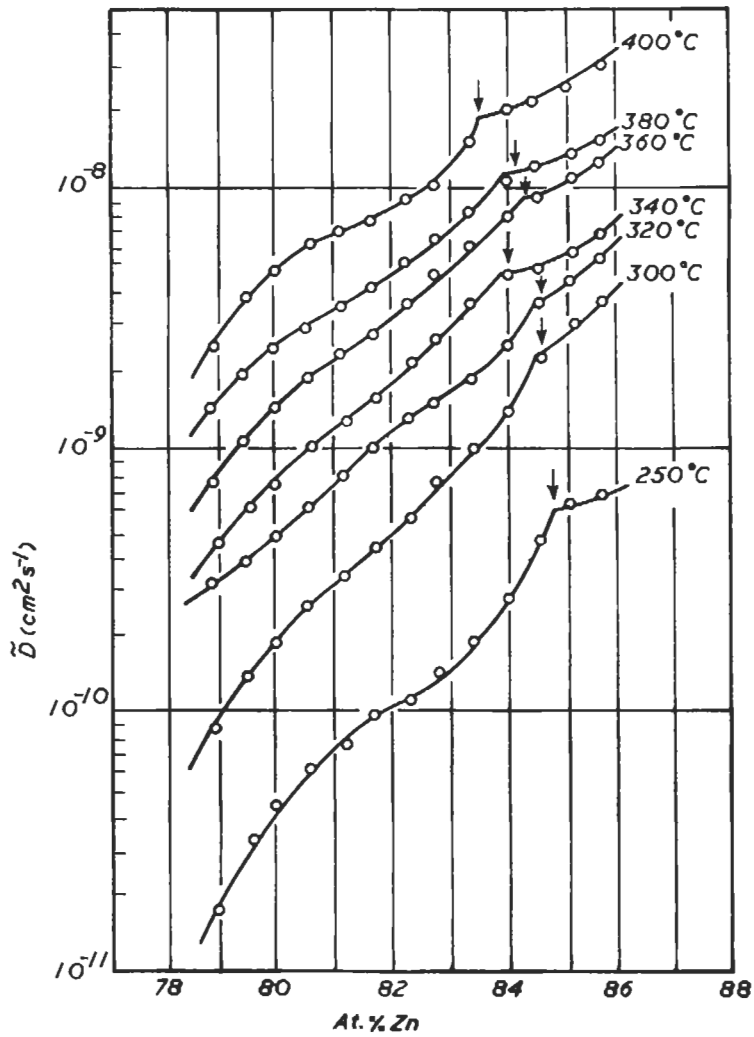


Figure 13.37 *Chemical diffusion in ε Cu-Zn alloys*[251]

Table 13.5 GRAIN BOUNDARY SELF-DIFFUSION

Element	A_{gb}	Q_{gb}	*Temp. range* °C	*Method*	*Ref.*
Ag	0.12 0.03	21.5 20.2	350–480	99.999% p.c. (F) 99.97% p.c. (F)	1
	0.026	18.4 ± 0.6	350–555	p.c. (W)*	17
	6.8×10^{-4}	11.8 ± 0.7	400–555	⟨100⟩ 16° *tilt* b.c. b'dies (W)*	
	—	~30	350–498	⟨112⟩ 18° *tilt* b.c. b'dies (W)	
	140×10^{-3} (D_P)	19.7	400–525	⟨100⟩ 9 to 28° *tilt* b.c. b'dies 99.98% (F)	2

Table 13.5 GRAIN BOUNDARY SELF-DIFFUSION—*continued*

Element	A_{gb}	Q_{gb}	*Temp. range* °C	*Method*	*Ref.*
	3.2×10^{-3} (D_p)	18.0	420–520	⟨100⟩, ⟨110⟩, ⟨111⟩ 2 to 30° *twist* b.c. b'dies, 99.999% (F)	3
		D_{gb} is anisotropic within a boundary			4
Au	6.2×10^{-3}	20.2 ± 0.5	367–444	99.999+, p.c. (W and S)	29
Zn	0.22	14.3 ± 0.2	75–160	99.999% p.c. (F)	5
	0.38	14.6 ± 0.2		99.97% p.c. (F)	
	—	12.3			6
Cd	1.0	13.0 ± 1.2	50–110	99.5% p.c. (F)	7
	$0.67^{+1.0}_{0.3}$	11.0 ± 0.66	51–135	99.9995% p.c. (S)	18
Sn	$(6.44^{+5.9}_{-4.9})\times10^{-2}$	9.55 ± 0.7	40–115	99.99% p.c. (F)	8
Pb	0.81	15.7	214–260	p.c. (F)	9
Pb	0.12	10.6 kcal/mol 44.4 kJ/mol	343–473 (K)	—	30
		D_{gb} is anisotropic within a boundary			10
	—	4.70 ± 0.41	120–220	⟨100⟩ 30° *tilt* b.c. b'dy	25
	—	4.10 ± 0.84		⟨100⟩ 20° *tilt* b.c. b'dy	
	—	5.75 ± 1.86		⟨100⟩ 14° *tilt* b.c. b'dy	
	—	9.12 ± 2.88		⟨100⟩ 10° *tilt* b.c. b'dy	
	—	8.00 ± 2.56		⟨100⟩ 10° *twist* b.c. b'dy	
				99.999+(F)	
Sb	$5.87^{+4.07}_{-2.41}$	23.1 ± 0.77	370–548	99.9% p.c. (W)	20
	$3.00^{+2.26}_{-1.29}$	22.2 ± 0.84	385–568	99.9999% p.c. (W)	
Te^{127m}	0.22	19.1 ± 1.6	280–390	g. b'dies p.c.	19
	1.89	21.6 ± 2.30	275–380	screw dislocations s.c.	
	0.88×10^{-2}	15.4 ± 1.15	253–401	edge dislocations s.c.	
				99.9999% (F)*	
Cr	—	46.0	1 000–1 350	p.c.	11
Fe					
(α)	13.0	40.0	580–660	99.7% p.c. (F)	12
	2.5	40.0	530–650	99.96% p.c. (F)	
	22.4	41.5	501–682	99.95%+p.c. (F)*	26
(γ)	5.0	39.0	923–1 016	99.7% p.c. (W)	13
	3.4	39.0	918–1 014	99.99% p.c. (W)	
	1.54	38.0	949–1 159	99.95%+p.c. (F)*	26
Co	0.15	39 ± 0.5	—	p.c.	14
Ni	$(1.75^{+2.1}_{-1.0})\,10^{-2}$	28.2 ± 2.0	850–1 100	99.85% p.c. (F)	15
	—	~29.9	700–1 100	⟨100⟩ 5° *tilt* b'dies (W)	16 and 28
	9.2×10^{-4}	24.9		⟨100⟩ 10° *tilt* b'dies (W)	
	8.0×10^{-3}	25.6		⟨100⟩ 20° *tilt* b'dies (W)	
	—	26.0 ± 1.5		⟨100⟩ 20–45° *tilt* b'dies (F)	
	0.44	40.7 ± 1.1	600–970	99.97% (W)	24
				⟨112⟩ {111} 10° b.c. *tilt* b'dies (edge dislocations)	
	0.52	44.9 ± 4.4		⟨111⟩ {111} 10° b.c. twist b'dies (screw dislocations)	
	20 (D_P)	36.8	500–600	99.999% edge dislocations in bent s.c.'s	27
W^{185}	6.66 ± 0.30	92.0 ± 2.0	1 400–2 200	99.992% (F)	21
		Q the same for sub-boundary (<10°) diffusion			
U	3.0×10^{2}	45.8	690–750	(β) p.c.	22
	2.0×10^{2}	42.7	850–1 050	(γ) p.c.	23

All values of A_{gb} are calculated assuming a grain boundary width $\delta = 5\times10^{-8}$ cm.
p.c. = polycrystals. b.c. = bicrystals. s.c. = single crystal.
Values of A_{gb}, and to a lesser extent of Q_{gb}, depend on the mathematical methods used to analyse the results:
(F) indicates results calculated from Fisher's solution of g.b. diffusion;
(W) indicates results calculated from Whipple's solution of g.b. diffusion:
(S) indicates results calculated from Suzuoka's solution;
()* indicates the results are reported calculated from more than one solution, in addition to the one listed;
(D_p) signifies that A_{gb} refers to dislocation pipe diffusion—*see* references 2 and 27.

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Table 13.6 SELF-DIFFUSION IN LIQUID METALS

Element	*A*	*Q*	*Temp. range* °C	*Method*	*Ref.*
Li	1.44×10^{-3}	12.0	465–723	IIIb(ii), Capillary	1 and 2
Na	8.6×10^{-4}	9.29	375–563	IVa(i), Capillary	2
K	7.6×10^{-4}	8.46	355–563	IVa(i), Capillary	2
$D=5.344\times10^{-10}T^{2}-2.443\times10^{-5}$			354–868	IIa(ii), Capillary	22
Rb	6.6×10^{-4}	8.29	330–503	Electrotransport method	2 and 3
$D=3.824\times10^{-10}T^{2}-1.479\times10^{-5}$			337–856	IIa(ii), Capillary	22
Cs	4.8×10^{-4}	7.79	323–473	Calculated	2 and 4
Cu	1.46×10^{-3}	40.7	1 413–1 543	IIIb(ii), Capillary	5
Agz5.8×10^{-4}	32.1	1 243–1 573	IIIb(ii), Capillary	6	
Zn	8.2×10^{-4}	21.3	723–893	IIIb(ii), Capillary	7
	1.2×10^{-3}	23.4	703–893	IIIb(ii), Capillary	8
Cd	3.62×10^{-4}	13.9	603–783	IIIb(ii), Capillary	9
	7.54×10^{-4}	18.5	603–773	IIIa(i), Capillary	23
Hg	$D=4.48\times10^{-10}T^{1.854}$		273–567	IIIb(ii), Capillary	11
$D=4.34\times10^{-9}T^{3/2}-4.81\times10^{-6}$			248–525	IIa(ii), shear cell	10
Ga	$D=2.2\times10^{-10}T^{2}$		292–556	IIa(ii), Capillary	12
$D=6.01\times10^{-9}T^{3/2}-1.60\times10^{-5}$			304–674	IIa(ii), Shear cell	13
In	2.89×10^{-4}	10.2	443–1 023	IIIb(ii), Capillary	14
Tl	3.17×10^{-4}	15.2	623–1 073	IIIb(ii), Capillary	15
Sn	3.24×10^{-4}	11.6	540–956	IIa(ii), Capillary	21
$D=[1.8+0.012(T-T_{M})]10^{-5}$			628–1 925	IIa(ii), Shear cell	16
	$D=6.85\times10^{-11}T^{2}$		543–1 048	IIa(ii), Capillary	17
Pb	2.37×10^{-4}	24.7	623–783	IIIb(ii), Capillary	9
Bi	8.3×10^{-5}	10.5	540–980	IIIb(ii), Capillary	18
Fe	1×10^{-2}	65.7	(a) 1 610–1 680	IIb(ii), Capillary	19
	4.3×10^{-3}	51.1	(b) 1 510–1 630		
Te	1.36×10^{-3}	23.7	710–873	IVb(ii), Capillary	20

(*a*) Average values. *A* and *Q* both increase with temperature.
(*b*) Supercooled.

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14 General physical properties

14.1 The physical properties of pure metals

Many physical properties depend on the purity and physical state (annealed, hard drawn, cast, etc.) of the metal. The data in Tables 14.1 and 14.2 refer to metals in the highest state of purity available, and are sufficiently accurate for most purposes. The reader should, however, consult the references before accepting the values quoted as applying to a particular sample.

Table 14.1 THE PHYSICAL PROPERTIES OF PURE METALS AT NORMAL TEMPERATURES

Metal	*Melting point* °C	*Boiling point* °C	*Density at* 20 °C $g cm^{-3}$‡	*Thermal conductivity* 0–100 °C $W m^{-1} K^{-1}$	*Mean specific heat* 0–100 °C $J kg^{-1} K^{-1}$	*Resistivity at* 20 °C μΩcm	*Temp. coeff. of resistivity* 0–100 °C $10^{-3} K^{-1}$	*Coefficient of expansion* 0–100 °C $10^{-6} K^{-1}$
Aluminium	660.323†	2520	2.70	238	917	2.67	4.5	23.5
Antimony	630.63†	1590	6.68	23.8	209	40.1	5.1	8–11
Arsenic	(817)	616	5.727	—	331	33.3	—	5.6
Barium	729	2130	3.5	—	285	60 (0 °C)	—	18
Beryllium	1287	2470	1.848	194	2052	3.3	9.0	12
Bismuth	217.403	1564	9.80	9	124.8	117	4.6	13.4
Cadmium	321.069†	767	8.64	103	233.2	7.3	4.3	31
Caesium	28.5	670	1.87	36.1(s)	234	20	4.8	97
Calcium	839	1484	1.54	125	624	3.7	4.57	22
Cerium	798	3430	6.75	11.9	188	85.4	8[7]	8
Chromium	1860	2680	7.1	91.3	461	13.2	2.14	6.5
Cobalt	1495†	2930	8.9	96	427	6.34	6.6	12.5
Copper	1084.62†	2560	8.96	397	386.0	1.694	4.3	17.0
Dysprosium	1500	(2630)	8.536	10.0	173	91	1.19	8.6
Erbrium	1530	(2600)	9.051	9.6	166	86	2.01	9.2
Gadolinium	1350	(3000)	α7.895 β7.80	8.8	298	134	0.9/1.76	6.4
Gallium	29.7646†	2205	5.91	41.0(s)	377	*	—	18.3
Germanium	937	2830	5.32	56.4	310	$\sim 89 \times 10^3$	—	5.75
Gold	1064.18†	2860	19.3[2]	315.5	130	2.20	4.0	14.1
Hafnium	2227	4600	13.1	22.9	147	32.2	4.4	6.0
Holmium	1461	2600	8.803	—	164	94	1.71	9.5**
Indium	156.5985†	2070	7.3	80.0	243	8.8	5.2	24.8
Iridium	2446†	4390	22.4	146.9	130.6	5.1	4.5	6.8
Iron	1536	2860	7.87	78.2	456	10.1	6.5	12.1
Lanthanum	920	(3420)	α6.174 β6.186 γ5.97	13.8	200	57	2.18	4.9
Lead	327.462†	1750	11.68	34.9	129.8	20.6	4.2	29.0
Lithium	181	1342	0.534	76.1	3517	9.29	4.35	56
Lutetium	1652	3327	9.842	—	154	68	—	125**
Magnesium	649	1090	1.74	155.5	1038	4.2	4.25	26.0
Manganese	1244	2060	7.4	7.8	486	160(α)	—	23

* *See* 'Electrical properties'.
** at 400 °C.
‡ Densities of higher allotropes not at 20 °C.
† Defined fixed point at ITS-90—see Chapter 16.

Table 14.1 THE PHYSICAL PROPERTIES OF PURE METALS AT NORMAL TEMPERATURES—*continued*

Metal	*Melting point* °C	*Boiling point* °C	*Density at* 20 °C $g cm^{-3}$ ‡	*Thermal conductivity* 0–100 °C $W m^{-1} K^{-1}$	*Mean specific heat* 0–100 °C $J kg^{-1} K^{-1}$	*Resistivity at* 20 °C μΩcm	*Temp. coeff. of resistivity* 0–100 °C $10^{-3} K^{-1}$	*Coefficient of expansion* 0–100 °C $10^{-6} K^{-1}$
Mercury	−38.87	357	13.546	8.65	138	95.9	1.0	61
Molybdenum	2615	4610	10.2	137	251	5.7	4.35	5.1
Neodymium	1024	(3060)	α7.004 β6.80	13.0	209	64	1.64	6.7
Nickel	1455†	2915	8.9	88.5	452	6.9	6.8	13.3
Niobium	2467	4740	8.6	54.1	268	16.0	2.6	7.2
Osmium	3030	5000	22.5	86.9	130	8.8	4.1	4.57
Palladium	1554†	2960	12.0	75.2	247	10.8	4.2	11.0
Platinum	1768†	3830	21.45	73.4	134.4	10.58	3.92	9.0
Plutonium	640	3235	19.84	8.4	142	146.5	—	55
Polonium	246	965	—	—	—	—	—	—
Potassium	63.2	759	0.86	104(s)	754	6.8	5.7	83
Praeseodymium	932	(3020)	α6.782 β6.64	11.7	192	68	1.71	4.8
Radium	700	1500	5	—	—	—	—	—
Rhenium	3180	5690	21.0	47.6	138	18.7	4.5	6.6
Rhodium	1962†	3700	12.4	148	243	4.7	4.4	8.5
Rubidium	38.8	688	1.53	58.3(s)	356	12.1	4.8	9.0
Ruthenium	2310	4120	12.2	116.3	234	7.7	4.1	9.6
Samarium	1072	1803	7.536 7.40	—	181	92	1.48	—
Scandium	1538	(2870)	2.99	—	558	66	—	12
Selenium	220.5	685	4.79	—	339	12	—	37
Silicon	1412	3270	2.34	138.5	729	10^3–10^6	—	7.6
Silver	961.78†	2163	10.5	425	234	1.63	4.1	19.1
Sodium	97.8	883	0.97	128	1227	4.7	5.5	71
Strontium	770	1375	2.6	—	737	23 (0 °C)	—	100
Tantalum	2980	5370	16.6	57.55	142	13.5	3.5	6.5
Terbium	1356	(2500)	8.272	—	172	116	—	7.0
Tellurium	450	988	6.24	3.8	134	1.6×10^5 (0 °C)	— —	1.7 ‖c axis 27.5 ⊥c axis
Thallium	304	1473	11.85	45.5	130	16.6	5.2	30
Thorium	1755	4290	11.5	49.2	100	14	4.0	11.2
Thulium	1543	1727	9.322	—	160	90	1.95	11.6**
Tin	231.928†	2270	7.3	73.2	226	12.6	4.6	23.5
Titanium	1667	3285	4.5	21.6	528	54	3.8	8.9
Tungsten	3420†	5555	19.3	174	138	5.4	4.8	4.5
Uranium	1132	4400	19.05(α) 18.89(β)	28	117	27	3.4	‡
Vanadium	1902	3410	6.1	31.6	498	19.6	3.9	8.3
Ytterbium	824	1427	6.977 6.54	—	145	28	1.30	25.0
Yttrium	1520	3300	4.478 4.25	10.2	309	53	2.71	10.8**
Zinc	419.527†	911	7.14	119.5	394	5.96	4.2	31
Zirconium	1852	4400	6.49	22.6	289	44	4.4	5.9

(s) = solid • *See* 'Electrical properties.' ‡ α-Uranium 23 ‖ *a* axis, −3.5 ‖ *b* axis, 17 ‖ *c* axis } 25–300 °C β-Uranium 4.6 ‖ *c* axis, 23 ⊥ *c* axis } 20–720 °C

** At 400 °C. ‡ Densities of higher allotropes not at 20 °C.

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Melting and boiling points (1) *see also* 'Thermochemical data' p. 8–1. Electrical resistivity (2,3) *see also* 'Electrical properties, p. 19–1. Specific heat (4,5) Thermal conductivity (6).

† Defined fixed point of ITS-90—see Chapter 16.

Table 14.2 THE PHYSICAL PROPERTIES OF PURE METALS AT ELEVATED TEMPERATURES

Metal	*Temperature* t °C	*Coefficient of expansion* 20–t °C 10^{-6} K^{-1}	*Resistivity at* t °C μΩ cm	*Thermal conductivity at* t °C W m^{-1} K^{-1}	*Specific heat at* t °C J kg^{-1} K^{-1}	*References*
Aluminium	20	—	2.67		900	7, 8, 9
	100	23.9	3.55		938	
	200	24.3	4.78	238	984	
	300	25.3	5.99		1 030	
	400	26.49	7.30		1 076	
Antimony	20	—	40.1	18.0	205	7, 10, 6
	100	8.4–11.0	59	16.7	214	
	500	9.7–11.6	154	19.7	239	
Beryllium	20	—	3.3	180	1 976	11
	100	12	5.3	152	2 081	
	200	13	10.5	130.2	(2 215)	
	300	14.5	11.1	117.7	(2 353)	
	500	16	21.8	103.0	(2 621)	
	700	17	26	85.8	(2 889)	
Bismuth	20	—	117	8.0	121	7, 12
	100	13.4	156	7.5	130	
	250	—	260	7.5	147	
Cadmium	20	—	7.3	84	230	7, 13, 14
	100	31.8	9.6	87.9	239	
	300	(38)	18.0	104.7	260	
Chromium	20	—	13.2	91.3	444	7, 15, 16
	100	6.6	18 (152 °C)	—	490	
	400	8.4	31 (407 °C)	76.2 (426 °C)	582	
	700	9.4	47 (652 °C)	67.4 (760 °C)	649	
Cobalt	20	—	5.68	—	434	42, 45
	100	12.3	9.30	—	453	
	200	13.1	13.88	—	478	
	300	13.6	19.78	—	502	
	400	14.0	26.56	—	527	
	600	—	40.2	—	575	
	800	—	58.6	—	716	
	1 000	—	77.4	—	800	
	1 200	—	91.9	—	883	
Copper	20	—	1.694	394	385	7, 17, 16, 18
	100	17.1	—	394	389	
	200	17.2	2.93	389	402	
	500	18.3	4.6 (497 °C)	341 (538 °C)	(427)	
	1 000	20.3	8.1 (977 °C)	244 (1 037 °C)	(473)	
Gold	20	—	2.2	293	126	7
	100	14.2	2.8	293	130	
	500	15.2	6.8	—	142	
	900	16.7	11.8	—	151	
Hafnium	20	—	35.5	(22.2)	144	43, 44, 48
	100	—	46.5	22.0	148	
	200	—	60.3	21.5	152	
	400	6.3	84.4	20.7	160	
	1 000	6.1	—	—	185	
	1 400	6.0	—	—	—	
	1 800	5.9	—	—	—	
Iridium	20	—	5.1	148 (0 °C)	130	19
	100	6.8	6.8	143	134	
	500	7.2	15.1	—	142	
	1 000	7.8	—	—	159	

Table 14.2 THE PHYSICAL PROPERTIES OF PURE METALS AT ELEVATED TEMPERATURES—*continued*

Metal	*Temperature* t °C	*Coefficient of expansion* 20–t °C $10^{-6}\,K^{-1}$	*Resistivity at* t °C $\mu\Omega$ cm	*Thermal conductivity at* t °C $W\,m^{-1}\,K^{-1}$	*Specific heat at* t °C $J\,kg^{-1}\,K^{-1}$	*References*
Iron	20	—	10.1	73.3	444	7, 20
	100	12.2	14.7	68.2	477	
	200	12.9	22.6	61.5	523	
	400	13.8	43.1	48.6	611	
	600	14.5	69.8	38.9	699	
	800	14.6	105.5	29.7	791	
Lead	20	—	20.6	34.8	130	7, 6, 11
	100	29.1	27.0	33.5	134	
	200	30.0	36.0	31.4	134	
	300	31.3	50	29.7	138	
Magnesium	20	—	4.2	167	1022	7
	100	26.1	5.6	167	1063	
	200	27.0	7.2	163	1110	
	400	28.9	12.1	130	1197	
Molybdenum	20	—	5.7	142	247	7, 21, 22, 23
	100	5.2	7.6	138	260	
	500	5.7	17.6	121	285	
	1000	5.75	31	105	310	
	1500	6.51	46	84	339 (mean)	
	2500	—	77	—	—	
Nickel	20	—	6.9	88	435	24
	100	13.3	10.3	82.9	477	
	200	13.9	15.8	73.3	528	
	300	14.4	22.5	63.6	578	
	400	14.8	30.6	59.5	519	
	500	15.2	34.2	62.0	535	
	900	16.3	45.5	—	595	
Niobium	20	—	14.6	—	268	42, 45
	200	7.19	25.0	56.5	271	
	400	7.39	36.6	60.7	284	
	600	7.56	48.1	65.3	292	
	800	7.72	59.7	—	301	
	1000	7.88	71.3	—	310	
Palladium	20	—	10.8	75	243	19
	100	11.1	13.8	74	247	
	500	12.4	27.5	—	268	
	1000	13.6	40	—	297	
Platinum	20	—	10.58	72	134	7, 19, 23, 25
	100	9.1	13.6	72	134	
	500	9.6	27.9	—	147	
	1000	10.2	43.1	67	159	
	1500	11.31	55.4	63	176	
Plutonium	20 $\alpha\rightarrow\alpha$	47	145.8	(8.4)	131	42, 45
	100 $\alpha\rightarrow\alpha$	203	141.6	—	138	
	200 $\alpha\rightarrow\beta$	173	107.8	—	145	
	300 $\alpha\rightarrow\gamma$	181	107.4	—	153	
	400 $\alpha\rightarrow\delta$	109	100.7	—	154	
	500 $\alpha\rightarrow\varepsilon$	101	110.6	—	144	
Rhenium	20	12.4 ‖-axis	18.7	48	134	26, 16, 27
	100	4.7 ⊥-axis	25		138	
	2500	7.29(2000 °C)	132	—	209(2527 °C)	
Rhodium	20	—	4.7	149	243	19
	100	8.5	6.2	147	255	
	500	9.8	14.6	—	289	
	1000	10.8	—	—	331	

Table 14.2 THE PHYSICAL PROPERTIES OF PURE METALS AT ELEVATED TEMPERATURES—*continued*

Metal	*Temperature* t°C	*Coefficient of expansion* 20–t°C $10^{-6}\,K^{-1}$	*Resistivity at* t°C $\mu\Omega cm$	*Thermal conductivity at* t°C $W\,m^{-1}\,K^{-1}$	*Specific heat at* t°C $J\,kg^{-1}\,K^{-1}$	*References*
Silver	20	—	1.63	419	234	7, 28
	100	19.6	2.1	419	222	
	500	20.6	4.7	(377)	(230)	
	900	22.4	7.6	—	(243)	
Tantalum	20	—	13.5	57	138	7, 29, 30,
	100	6.5	17.2	54	142	31, 32
	500	6.6	35	—	151	
	1 500	—	71	—	167	
	2 500	—	102	—	234(2 727°C)	
Thallium	20	—	16.6	46	134	33, 6
	100	30	—	45	138	
	200	—	—	45	142	
Tin	20	—	12.6	65	222	7, 34
	100	23.8	15.8	63	239	
	200	24.2	23.0	60	260	
Titanium	20	—	54	16	519	35, 36
	100	8.8	70	15	540	
	200	9.1	88	15	569	
	400	9.4	119	14	619	
	600	9.7	152	13	636	
	800	9.9	165	(13)	682	
Tungsten	20	—	5.4	167	134	37, 33
	100	4.5	7.3	159	138	38
	500	4.6	18	121	142	
	1 000	4.6	33	111	151	
	2 000	5.4	65	93	—	
	3 000	6.6	100	—	—	
Uranium	20 α	—	30	27	116	Expansion
	600 α	—	59	38	186	anisotropic
	700 β	—	55.5	40	176	42, 45
	800 γ	—	54	42.3	160	
Vanadium	20	—	24.8	—	492	42, 45
	100	8.3	31.5	31	505	
	500	9.6	—	36.8	570	
	700	—	—	35.2	603	
	900	10.4	—	—	636	
Zinc	20	—	5.96	113	389	39, 13, 40,
	100	31	7.8	109	402	41, 6
	200	33	11.0	105	414	
	300	34	13.0	101	431	
	400	—	16.5	96	444	

REFERENCES TO TABLES 14.1 AND 14.2

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14.2 The physical properties of liquid metals

Table 14.3a THE PHYSICAL PROPERTIES OF LIQUID METALS
Density, surface tension and viscosity

The values of the properties listed in Table 14.3a are the weighted mean of the experimental values due to the investigators listed, usually in order of the reliance placed on their results, in the column of references. The references are grouped, and relate to density, surface tension and viscosity in that order. The properties given in parentheses are estimates.

14.2.1 Density

The variation of the density D of most liquid metals with temperature t is found to be well represented by a linear equation

$$D = D_0 + (t - t_0)\,(\mathrm{d}D/\mathrm{d}t)$$

where D_0 is the density of the liquid metal at its melting point t_0.

14.2.2 Surface tension

The surface tension γ of most liquids can be represented over temperature ranges of usual interest by the linear equation

$$\gamma = \gamma_0 + (t - t_0)\,(\mathrm{d}\gamma/\mathrm{d}t)$$

14.2.3 Viscosity

For most liquid metals the variation of viscosity η with temperature T(K) may be written

$$\eta = \eta_0 \exp(E/RT)$$

where η_0 and E are constants, and are given in the table, and R is the gas constant, 8.3144 J K^{-1} mol^{-1}.

Table 14.3a THE PHYSICAL PROPERTIES OF LIQUID METALS

	Temp	*Density*		*Surface tension*		*Viscosity*			
Metal	t_0 °C	D_0 g cm^{-3}	dD/dt mg cm^{-3} K^{-1}	γ_0 mN m^{-1}	dγ/dt mN m^{-1} K^{-1}	η_{mp} mN s m^{-2}	η_0 mN s m^{-2}	E kJ mol^{-1}	*References*
Ag	960.7	9.346	−0.907	903	−0.16	3.88	0.453 2	22.2	1, 26, 27/86/90, 91
Al	660.0	2.385	−0.28	914	−0.35	1.30	0.149 2	16.5	2–6/86/90, 91
As	817	5.22	−0.535	—	—	—	—	—	7/–/–
Au	1 063	17.36	−1.5	1 140	−0.52	5.0	1.132	15.9	9, 8/86/90, 91
B	2 077	2.08	—	1 070	—	—	—	—	10/86/–
Ba	727	3.321	−0.526	224	−0.095	—	—	—	11, 12/89/–
Be	1 283	1.690	−0.116 2	1 390	(−0.29)	—	—	—	13/86/–
Bi	271	10.068	−1.33	378	−0.07	1.80	0.445 8	6.45	14/86/90, 91
Ca	865	1.365	−0.221	361	−0.10	1.22	0.065 1	27.2	12/86/90, 91
Cd	321	8.02	−1.16	570	−0.26	2.28	0.300 1	10.9	15, 16, 17, 18, 77/86/90, 91
Ce	804	6.685	−0.227	740	−0.33	2.88	—	—	19–22/86/59
Co	1 493	7.76	−0.988	1 873	−0.49	4.18	0.255 0	44.4	23, 24, 25/86/90, 91
Cr	1 875	6.28	−0.30	1 700	(−0.32)	—	—	—	25, 29/86/–
Cs	28.6	1.854	−0.638 1	69	−0.047	0.68	0.102 2	4.81	30/30, 84/90, 91
Cu	1 083	8.000	−0.801	1 285	−0.13	4.0	0.300 9	30.5	31, 32, 33, 26, 34, 8/73, 34, 87, 88/90, 91
Fe	1 536	7.015	−0.883	1 872	−0.49	5.5	0.369 9	41.4	36, 23, 25, 33, 37/86/90, 91
Fr	18	(2.35)	(−0.792)	(62)	(−0.044)	(0.765)	—	—	38/38/38
Ga	29.8	6.09	−0.60	718	−0.10	2.04	0.435 9	4.00	39, 40/86/90, 91
Gd	1 312	(7.14)	—	810	−0.16	—	—	—	86/86/–
Ge	934	5.60	−0.625	621	−0.26	0.73	—	—	41, 42, 28, 13, 43 /86/94
Hf	1 943	11.1	—	1 630	(−0.21)	—	—	—	86/86–
Hg	−38.87	13.691	−2.436	498	−0.20	2.10	0.556 5	2.51	45, 46/86/90, 91
	0	13.595 1	average						
	20	13.545 9	over						
			0–100 °C						
	100	13.351 5							
In	156.6	7.023	−0.679 8	556	−0.09	1.89	0.302 0	6.65	47/86/90, 91
Ir	2 443	(20.0)	—	2 250	(−0.31)	—	—	—	48/86/–
K	63.5	0.827 0	−0.228 5	111.0	−0.062 5	0.51	0.134 0	5.02	30/30/90, 91
La	930	5.955	−0.237	720	−0.32	2.45	—	—	59/85/59
Li	180.5	0.525	−0.186 3	395	−0.150	0.57	0.145 6	5.56	30/30/90, 91
Mg	651	1.590	−0.264 7	559	−0.35	1.25	0.024 5	30.5	49–51/86/90, 91
Mn	1 241	5.73	−0.7	1 090	−0.2	—	—	—	52/53/–
Mo	2 607	(9.34)	—	2 250	(−0.30)	—	—	—	48, 54/86/–
Na	96.5	0.927	−0.236 1	195	−0.089 5	0.68	0.152 5	5.24	30/30/90, 91
Nb	2 468	(7.83)	—	1 900	(−0.24)	—	—	—	48/86/–
Nd	1 024	6.688	−0.528	689	−0.09	—	—	—	22/86/–
Ni	1 454	7.905	−1.160	1 778	−0.38	4.90	0.166 3	50.2	36, 25, 55, 37, 56, 23, 34/86/90, 91
Os	2 727	(20.1)	—	2 500	(−0.33)	—	—	—	48/86/–

Table 14.3a THE PHYSICAL PROPERTIES OF LIQUID METALS—*continued*

	Temp	*Density*		*Surface tension*		*Viscosity*			
Metal	t_0 °C	D_0 g cm^{-3}	dD/dt mg cm^{-3} K^{-1}	γ_0 mN m^{-1}	$d\gamma/dt$ mN m^{-1} K^{-1}	η_{mp} mN s m^{-2}	η_0 mN s m^{-2}	E kJ mol^{-1}	*References*
P	44	—	—	52	—	1.71	—	—	–/86/95
Pb	327	10.678	−1.3174	468	−0.13	2.65	0.4636	8.61	57, 58, 15/86/90, 91
Pd	1552	10.49	−1.266	1500	(−0.22)	—	—	—	26/86/–
Pr	935	6.611	−0.240	—	—	2.80	—	—	59, 20/–/59
Pt	1769	19	−2.9	1800	(−0.17)	—	—	—	26, 60/86/–
Pu	640	16.64	−1.450	550	(−0.10)	6.0	1.089	5.59	61, 62/86/92
Rb	38.9	1.437	−0.486	83	−0.052	0.67	0.0940	5.15	30/30, 84/90, 91
Re	3158	(18.8)	—	2700	(−0.34)	—	—	—	48, 54/86/–
Rh	1966	10.8	—	2000	(−0.30)	—	—	—	48/63/86/–
Ru	2427	(10.9)	—	2250	(−0.31)	—	—	—	48/86/–
S	119	1.819	−0.800	61	−0.07	~12	—	—	64/86/95
Sb	630.5	6.483	−0.565*	367	−0.05	1.22	0.0812	22.0	65, 13/86/90, 91
Se	217	3.989	−1.44	106	−0.1	24.8	—	—	66–69/86/94
Si	1410	2.51	−0.32	865	(−0.13)	0.94	—	—	14, 34, 70/86/94
Sn	232	7.000	−0.6127	544	−0.07	1.85	0.5382	—	71/86/90, 91
Sr	770	2.48	—	303	−0.10	—	—	—	72/86/–
Ta	2977	(15.0)	—	2150	(−0.25)	—	—	—	48/86/–
Te	451	5.71	−0.360	180	(−0.06)	~2.14	—	—	27, 73, 43, 74/86/94
Th	1691	10.5	—	978	(−0.14)	—	—	—	72/86/–
Ti	1685	4.11	−0.702	1650	(−0.26)	5.2	—	—	75/86/93
Tl	302	11.280	−1.43	464	−0.08	2.64	0.2983	10.5	76–78/86/90, 91
U	1133	17.90	−1.031	1550	−0.14	6.5	0.4848	30.4	79/96/90, 91
V	1912	5.7	—	1950	(−0.31)	—	—	—	75/48/86
W	3377	(17.6)	—	2500	(−0.29)	—	—	—	48, 54, 80/86/–
Yb	824	—	—	—	—	1.07	—	—	–/–/94
Zn	419	6.575	−1.10	782	−0.17	3.85	0.4131	12.7	73, 81, 16, 82, 83/86/90, 91
Zr	1850	(5.8)	—	1480	(−0.20)	8.0	—	—	44, 48, 75/86/93

* For antimony the simple linear equation is adequate to about 1000 °C. However, the results for all the temperatures within the liquid range are better represented by the equation

$$D = 6.596 + 2.022 \times 10^{-4} T - 3.629 \times 10^{-7} T^2$$

where T is in degrees K (ref. 65).

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Table 14.3b THE PHYSICAL PROPERTIES OF LIQUID METALS
Specific heat, thermal conductivity, and electrical resistivity

Element	*Temperature* °C	*Specific heat* $J\,g^{-1}\,K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$	*Electrical resistivity* $\mu\Omega\,m$	*Reference*
Ag	960.7	0.283	174.8	0.172 5	1
	1 000	0.283	176.5	0.176 0	
	1 100	0.283	180.8	0.184 5	
	1 200	0.283	185.1	0.193 5	
	1 300	0.283	189.3	0.202 3	
	1 400	—	193.5	0.211 1	
Al	660	1.08	94.03	0.242 5	1
	700	1.08	95.37	0.248 3	
	800	1.08	98.71	0.263 0	
	900	1.08	102.05	0.277 7	
	1 000	—	105.35	0.292 4	
As	817	—	—	(2.10)	1
Au	1 063	(0.149)	104.44	0.312 5	1, 21
	1 100	(0.149)	105.44	0.318 0	
	1 200	(0.149)	108.15	0.331 5	
	1 300	(0.149)	110.84	0.348 1	
	1 400	(0.149)	113.53	0.363 1	
B	2 077	2.91	—	(2.10)	1, 21
Ba	727	0.228	—	1.33	2, 21
Be	1 283	3.48	—	(0.45)	1, 21
Bi	271	0.146	17.1	1.290	3, 4, 8, 21
	300	0.143	15.5		
	400	0.147 5	15.5		
	500	0.137 5	15.5		
	600	0.133 6	15.5		
	700	—	15.5		
Ca	865	(0.775)	—	(0.250)	1, 21
Cd	321	0.264	42	0.337	2, 5, 6
	400	0.264	47	0.343 0	
	500	0.264	54	0.351 0	
	600	0.264	(61)	0.360 7	
Ce	804	0.25	—	1.268	15, 21
	1 000	0.25	—	1.294	
	1 200	0.25	—	1.310	
Co	1 493	(0.59)	—	1.02	2, 3, 21

Table 14.3b THE PHYSICAL PROPERTIES OF LIQUID METALS—*continued*

Element	*Temperature* °C	*Specific heat* $J g^{-1} k^{-1}$	*Thermal conductivity* $W m^{-1} K^{-1}$	*Electrical resistivity* $\mu\Omega m$	*Reference*
Cr	(1 903)	(0.78)	—	(0.316)	1, 21
Cs	28.6	0.28	19.7	0.370	1, 7
	100	0.265	20.2	0.450	
	200	0.240	20.8	0.565	
	400	0.21	20.2	0.810	
	600	0.22	18.3	1.125	
	800	0.25	16.1	1.570	
	1 600	—	4.0	—	
Cu	1 083	0.495	165.6	0.200	1, 21
	1 100	0.495	166.1	0.202	
	1 200	0.495	170.1	0.212	
	1 400	0.495	176.3	0.233	
	1 600	0.495	180.4	0.253	
Fe	1 536	(0.795)	—	1.386	9, 10, 21
Fr	18	(0.142)	—	(0.87)	1, 11
	700	(0.134)	—		
Ga	29.8	0.398	(25.5)	0.26	4, 8, 9
	100	0.398	30.0	0.27	12, 13,
	200	0.398	35.0	0.28	21
	300	0.398	(39.2)	0.30	
Gd	(1 350)	(0.213)	—	(0.278)	1, 21
Ge	934	(0.404)	—	0.672	8, 9, 14,
	1 000	(0.404)	—	0.727	21
Hf	(2 227)	—	—	(2.18)	1
Hg	−38.87	(0.142)	6.78	0.905	1, 8, 21
	0	(0.142)	7.61	0.940	
	20	0.139	8.03	0.957	
	100	0.137	9.47	1.033	
	500	(0.137)	12.67	1.600	
	1 000	—	8.86	3.77	
	1 460 (critical temp.)		~0.000 4	~1 000	
Ho	1 500	(0.203)	—	(1.93)	1, 21
In	156.6	(0.259)	(42)	0.323 0	16, 21
	200	(0.259)		0.333 9	
	400	(0.259)		0.436 1	
	600	(0.259)		(0.513 1)	
K	63.5	0.820	53.0	0.136 5	1, 7
	100	0.810	51.7	0.154	
	200	0.790	47.7	0.215	
	500	0.761	37.8	0.444	
	1 000	(0.838)	24.4	(0.110)	
	1 500	—	15.5		
La	930	(0.057 5)	(21.0)	1.38	17, 21
	1 000	(0.057 5)	—	1.43	
	1 100	(0.057 5)	—	1.50	
	1 200	(0.057 5)	—	1.56	
Li	180.5	4.370	46.4	0.240	1, 7, 9
	200	4.357	47.2	—	
	400	4.215	53.8	—	
	600	4.165	57.5	—	
	800	4.148	58.6	—	
	1 000	4.147	58.4	—	
	1 600	(4.36)	52.0	—	

Table 14.3b THE PHYSICAL PROPERTIES OF LIQUID METALS—*continued*

Element	*Temperature* °C	*Specific heat* $J g^{-1} K^{-1}$	*Thermal conductivity* $W m^{-1} K^{-1}$	*Electrical resistivity* $\mu\Omega m$	*Reference*
Mg	650	(1.36)	78	0.274	4, 5, 21
	700	(1.36)	81	0.277	
	800	(1.36)	88	0.282	
	1 000	(1.36)	100	—	
Mn	124	0.838	—	0.40	1, 9, 21
Mo	2 607	0.57	—	(0.605)	1, 21
Na	97	1.386	89.7	0.096 4	1, 7
	100	1.385	89.6	0.099	
	200	1.340	82.5	0.134	
	400	1.278	71.6	0.224	
	600	1.255	62.4	0.326	
	800	1.270	53.7	0.469	
	1 000	(1.316)	45.8	—	
	1 200	(1.405)	38.8	—	
Nb	2 468	—	—	(1.05)	1
Nd	1 024	0.232	—	(1.26)	1, 21
Ni	1 454	0.620	—	0.850	9, 21
P (black)	44	—	—	(2.70)	1
Pb	327	0.152	15.4	0.948 5	5, 16
	400	0.144	16.6	0.986 3	
	500	0.137	18.2	1.034 4	
	600	0.135	19.9	(1.082 5)	
	800	—	—	(1.169)	
	1 000	—	—	(1.263)	
Po	254	—	—	(3.98)	1
Pr	935	(0.238)	—	(1.38)	1, 21
Pt	1 770	(0.178)	—	(0.73)	1, 21
Pu	640	—	—	(1.33)	1
Ra	960	(0.136)	—	(1.71)	1, 21
Rb	38.8	0.398	33.4	0.228 3	1, 7
	100	0.383	33.4	0.273 0	
	200	0.364	31.6	0.366 5	
	500	0.348	26.1	0.689 0	
	1 000	(0.378)	17.0	(1.71)	
	1 500	—	8.0	(5.32)	
Re	3 158	—	—	(1.45)	1
Ru	2 427	—	—	(0.84)	1
S	119	0.984	—	$> 10^{10}$	2, 21
Sb	630.5	(0.258)	21.8	1.135	4, 9, 21
	700	(0.258)	21.3	1.154	
	800	(0.258)	20.9	1.181	
	1 000	(0.258)	—	1.235	
Sc	1 539	(0.745)	—	(1.31)	1, 21
Se	217	0.445	0.3	$\sim 10^6$	2, 18, 21
Si	1 410	1.04	—	0.75	1, 2, 14,
	1 500	1.04	—	0.82	21
	1 600	1.04	—	0.86	
Sm	1 072	(0.223)	—	(1.90)	1, 21
Sn	232	0.250	30.0	0.472 0	5, 16, 21
	300	0.242	31.4	0.490 6	
	400	0.241	33.4	0.517 1	
	500	(0.24)	35.4	0.543 5	
	1 000	(0.26)	—	(0.670)	

Table 14.3b THE PHYSICAL PROPERTIES OF LIQUID METALS—*continued*

Element	*Temperature* °C	*Specific heat* $J g^{-1} K^{-1}$	*Thermal conductivity* $W m^{-1} K^{-1}$	*Electrical resistivity* μΩ m	*Reference*
Sr	770	0.354	—	(0.58)	1, 21
Ta	(2 996)	—	—	(1.18)	1
Tb	1 365	—	—	(2.44)	1
Te	450	(0.295)	2.5	5.50	2, 9, 14
	500	(0.295)	3.0	4.80	19, 21
	600	(0.295)	4.1	4.30	
	800	(0.295)	(6.2)	(3.9)	
	1 000	(0.295)	—	(3.8)	
Ti	1 685	(0.700)	—	(1.72)	1, 21
Tl	303	0.149	(24.6)	0.731	9, 21
	400	0.149		0.759	
	500	0.149	—	0.788	
Tm	1 600	—	—	(1.88)	1
U	1 133	(0.161)	—	0.636	20, 21
	1 200	(0.161)	—	0.653	
	1 300	(0.161)	—	(0.678)	
V	1 912	(0.780)	—	(0.71)	1, 21
W	3 377	—	—	(1.27)	1
Y	1 530	(0.377)	—	(1.04)	1, 21
Yb	824	—	—	(1.64)	1
Zn	419.5	0.481	49.5	0.374	5, 9
	500	0.481	54.1	0.368	
	600	0.481	59.9	0.363	
	800	0.481	(60.7)	0.367	
Zr	1 850	(0.367)	—	(1.53)	1, 21

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14.3 The physical properties of aluminium and aluminium alloys

Table 14.4a THE PHYSICAL PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOYS AT NORMAL TEMPERATURES

			Sand cast				
Material	*Nominal composition* %		*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 100 °C W m^{-1} K^{-1}	*Resistivity* μΩ m	*Modulus of elasticity* MPa ×10^3
Al	Al	99.5	2.70	24.0	218	3.0	69
	Al	99.0	2.70	24.0	209	3.1	–
Al–Cu	Cu	4.5	2.75	22.5	180	3.6	71
	Cu	8	2.83	22.5	138	4.7	–
	Cu	12	2.93	22.5	130	4.9	–
Al–Mg	Mg	3.75	2.66	22.0	134	5.1	–
	Mg	5	2.65	23.0	130	5.6	–
	Mg	10	2.57	25.0	88	8.6	71
Al–Si	Si	5	2.67	21.0	159	4.1	71
	Si	11.5	2.65	20.0	142	4.6	–
Al–Si–Cu	Si	10	2.74	20.0	100	6.6	71
	Cu	1.5					
	Si	4.5	2.76	21.0	134	4.9	71
	Cu	3					
Al–Si–Cu–Mg*	Si	17	2.73	18.0	134	8.6	88
	Cu	4.5					
	Mg	0.5					
Al–Cu–Mg–Ni (Yalloy)	Cu	4	2.78	22.5	126	5.2	71
	Mg	1.5					
	Ni	2					
Al–Cu–Fe–Mg	Cu	10	2.88	22.0	138	4.7	71
	Fe	1.25					
	Mg	0.25					
Al–Si–Cu–Mg–Ni (Lo–Ex)	Si	12	2.71	19.0	121	5.3	71
	Cu	1					
	Mg	1					
	Ni	2					
	Si	23	2.65	16.5	107	–	88
	Cu	1					
	Mg	1					
	Ni	1					

*Die cast.

Table 14.4b THE PHYSICAL PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOYS AT NORMAL TEMPERATURES

					Wrought					
Specification	*Nominal composition* %		*Condition**		*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 100 °C W m^{-1} K^{-1}	*Resistivity* μΩ cm	*Temp. coeff. of resistance* 20–100 °C	*Modulus of elasticity* MPa ×10^3
1199	Al	99.992	Sheet	H111			239	2.68	0.0042	69
				H18	2.70	23.5	234	2.70	0.0042	69
			Extruded				239	2.68	0.0042	69
1080A	Al	99.8	Sheet	H111			234	2.74	0.0042	69
				H18	2.70	23.5	230	2.76	0.0042	69
			Extruded				230	2.79	0.0041	69
1050A	Al	99.5	Sheet	H111			230	2.80	0.0041	69
				H18	2.71	23.5	230	2.82	0.0041	69
			Extruded				226	2.85	0.0041	69
1200	Al	99	Sheet	H111			226	2.87	0.0040	69
				H18	2.71	23.5	226	2.89	0.0040	69
			Extruded				226	2.86	0.0040	69
2014A	Cu	4.4		T4	2.8	22	142	5.3		74
	Mg	0.7		T6	2.8	22	159	4.5		
	Si	0.8								
	Mn	0.75								
2024	Cu	4.5		T3	2.77	23		5.7		73
	Mg	1.5		T6	2.77	23	151	5.7		73
	Mn	0.6								
2090	Cu	2.7		T8	2.59	23.6	88.2	9.59		76
	Li	2.3								
	Zr	0.12								
2091	Cu	2.1		T8	2.58	23.9	84	9.59		75
	Li	2.0								
	Mg	1.50								
	Zr	0.1								

Table 14.4b THE PHYSICAL PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOYS AT NORMAL TEMPERATURES

Wrought

Specification	*Nominal composition %*		*Condition**		*Density* g cm^{-3}	*Coefficient of expansion* 20–100 °C 10^{-6} K^{-1}	*Thermal conductivity* 100 °C W m^{-1} K^{-1}	*Resistivity* μΩ cm	*Temp. coeff. of resistance* 20–100 °C	*Modulus of elasticity* MPa ×10^3
3103	Mn	1.25	Sheet	H111						
				H12						
				H14	2.74	23.0	180	3.9	0.0030	69
				H16						
				H18						
			Extruded				151	4.8	0.0024	–
5083	Mg	4.5	Sheet	H111	2.67	24.5	109	6.1	0.0019	71
	Mn	0.7		H12						
	Cr	0.15		H14						
5251	Mg	2.0	Sheet	H111	2.69	24	155	4.7	0.0025	70
	Mn	0.3		H13						
				H16						
			Extruded				147	4.9	0.0023	–
5154A	Mg	3.5	Sheet	H111			142	5.3	0.0021	70
				H14	2.67	23.5	138	5.4	0.0021	–
			Extruded				134	5.7	0.0019	–
5454	Mg	2.7	Sheet	H111	2.68	24	147	5.1		70
	Mn	0.75		H22						
	Cr	0.12		H24						
Al–Li	Li	2.0	Sheet	T6	2.56	–	–	–	–	77
Al–Mg–Li	Mg	3.0	Sheet	T6	2.52	–	–	–	–	79
	Li	2.0								
Al–Li–Mg	Li	3.0	Sheet	T6	2.46	–	–	–	–	84
	Mg	2.0								
6061	Mg	1.0	Bar	H111	2.7	23.6	180			68.9
	Si	0.6		T4	2.7	23.6	154			68.9
	Cu	0.2		T6	2.7	23.6	167			68.9
	Cr	0.25								
6063	Mg	0.5	Extruded	T4	2.70	23.0	193	3.5	0.0033	71
	Si	0.5		T6			201	3.3	0.0035	–
6063A	Mg	0.5	Bar	T4	2.7	24	197	3.5		69
	Si	0.5		T5		24	209	3.2		69
				T6		24	201	3.3		69
6082	Mg	1.0	Bar/Extruded	T4	2.7	23	172	4.1	0.0031	69
	Si	1.0		T6	2.7	23	184	3.7	0.0031	69
	Mn	0.7								
6082	Mg	1.0	Sheet	T4			188	3.6	0.0033	69
	Si	1.0		T6	2.69	23.0	193	3.4	0.0035	–
6463	Mg	0.65	Bar	T5	2.71	23.4	209	3.1		69
	Si	0.4		T6	2.71	23.4	201	3.3		69
Al–Cu–Mg–Si	Cu	4.0	Sheet	T6	2.80	22.5	147	5.0	0.0023	73
(Duralumin)	Mg	0.6								
	Si	0.4								
	Mn	0.6								
	Cu	4.5	Sheet	T4	2.81	22.5	147	5.2	0.0022	73
	Mg	0.5		T6			159	4.5	0.0026	–
	Si	0.75								
	Mn	0.75								
Al–Cu–Mg–Ni	Cu	4.0	Forgings	T6	2.78	22.5	151	4.9	0.0023	72
(Yalloy)	Mg	1.5								
	Ni	2.0								
Al–Si–Cu–Mg	Si	12.0	Forgings	T6	2.66	19.5	151	4.9	0.0023	79
(Lo–Ex)	Cu	1.0								
	Mg	1.0								
	Ni	1.0								
Al–Zn–Mg	Zn	10.0	Forgings		2.91	23.5	151	4.9	0.0023	–
	Cu	1.0								
	Mn	0.7								
	Mg	0.4								
7075	Zn	5.7	Extrusion	T6	2.80	23.5	130	5.7	0.0020	72
	Mg	2.6								
	Cu	1.6								
	Cr	0.25								
8090	Li	2.5	Plate		2.55	21.4	93.5	9.59		77
	Cu	1.3								
	Mg	0.95								
	Zr	0.1								

H111 = Annealed.
H12,22 = Quarter hard.
H14,24 = Half hard.
H16,26 = Three-quarters hard.
H18,28 = Hard.

T4 = Solution treated and naturally aged.
T6 = Solution treated and artificially aged.

Table 14.4b THE PHYSICAL PROPERTIES OF ALUMINIUM AND ALUMINIUM ALLOYS AT NORMAL TEMPERATURES—*continued*

Wrought

Specification	*Nominal composition* %	*Condition**		*Density* g cm^{-3}	*Coefficient of expansion* 20–100°C 10^{-6} K^{-1}	*Thermal conductivity* 100°C W m^{-1} K^{-1}	*Resistivity* μΩ cm	*Temp. coeff. of resistance* 20–100°C	*Modulus of elasticity* MPa × 10^3
Al–Cu–Mg–Si (Duralumin)	Cu 4.0 Mg 0.6 Si 0.4 Mn 0.6	Sheet	TF	2.80	22.5	147	5.0	0.002 3	73
	Cu 4.5 Mg 0.5 Si 0.75 Mn 0.75	Sheet	TB TF	2.81	22.5	147 159	5.2 4.5	0.002 2 0.002 6	73 —
Al–Cu–Mg–Ni (Yalloy)	Cu 4.0 Mg 1.5 Ni 2.0	Forgings	TF	2.78	22.5	151	4.9	0.002 3	72
Al–Si–Cu–Mg (Lo–Ex)	Si 12.0 Cu 1.0 Mg 1.0 Ni 1.0	Forgings	TF	2.66	19.5	151	4.9	0.002 3	79
Al–Zn–Mg	Zn 10.0 Cu 1.0 Mn 0.7 Mg 0.4	Forgings		2.91	23.5	151	4.9	0.002 3	—
7075	Zn 5.7 Mg 2.6 Cu 1.6 Cr 0.25	Extrusion	TF	2.80	23.5	130	5.7	0.002 0	72
8090	Li 2.5 Cu 1.3 Mg 0.95 Zr 0.1	Plate		2.55	21.4	93.5	9.59		77

*O = Annealed.
H12, 22 = Quarter hard.
H14, 24 = Half hard.
H16, 26 = Three-quarters hard.
H18, 28 = Hard.
T4 = Solution treated and naturally aged.
T6 = Solution treated and artificially aged.
See also pp. 22-1 and 22-2.

14.4 The physical properties of copper and copper alloys

Table 14.5 THE PHYSICAL PROPERTIES OF COPPER AND COPPER ALLOYS AT NORMAL TEMPERATURES

Material	*Composition* %	*Density* g cm^{-3}	*Melting point of liquidus* °C	*Coefficient of expansion* 25–300°C 10^{-6} K^{-1}	*Electrical conductivity* 20°C %IACS*	*Thermal conductivity* W m^{-1} K^{-1}	*Refs.*
Oxygen-free high conductivity copper	Cu 99.99+	8.94	1083	17.7	101.5	399	1
Tough pitch HC copper	O_2 0.03	8.92	1083	17.7	101.5	397	2,3,4
Phosphorus-deoxidized non-arsenical copper	P 0.005–0.012	8.94	1083	17.7	85–96	341–395	5
	P 0.013–0.050	8.94	1083	17.7	70–90	298–372	5
Deoxidized arsenical copper	P 0.03 As 0.35	8.94	1082	17.4	45	177	2
Silver bearing copper	O_2 0.02 Ag 0.05	8.92	1079	17.7	101	397	2,3

Table 14.5 THE PHYSICAL PROPERTIES OF COPPER AND COPPER ALLOYS AT NORMAL TEMPERATURES—*continued*

Material	*Composition* %	*Density* g cm^{-3}	*Melting point of liquidus* °C	*Coefficient of expansion* 25–300°C 10^{-6} K^{-1}	*Electrical conductivity* 20°C %IACS*	*Thermal conductivity* W m^{-1} K^{-1}	*Refs.*
Tellurium copper	Cu 99.5 Te 0.5	8.94	1082	17.7	98	382	2
Chromium copper	Cu 99.4 Cr 0.6	8.89	1081	17	45(1) 82(2)	167 188	6
Beryllium copper	Be 1.85 Co 0.25	8.25	1000	17	17(1) 23(2)	84 105	7
	Be 0.5 Co 2.5	8.75	1060	17	23(1) 47(2)	126 210	7
Cadmium copper	Cu 99.2 Cd 0.8	8.94	1080	17	85	376	6
Sulphur copper	Cu 99.65 S 0.35	8.92	1075	17	95	373	5
Cap copper	Cu 95 Zn 5	8.85	1065	18.1	56	234	5
Gilding metals CuZn10	Cu 90 Zn 10	8.80	1040	18.2	44	188	5
CuZn15	Cu 85 Zn 15	8.75	1020	18.7	37	159	5
CuZn20	Cu 80 Zn 20	8.65	1000	19.1	32	138	5
Brass CuZn30	Cu 70 Zn 30	8.55	965	19.9	28	121	5
CuZn33	Cu 67 Zn 33	8.50	940	20.2	27	121	5
CuZn37	Cu 63 Zn 37	8.45	920	20.5	26	125	5
CuZn40	Cu 60 Zn 40	8.40	900	20.8	28	126	5
Aluminium brass CuZn22Al2	Cu 76 Zn 22 Al 2	8.35	1010	18.5	23	101	5
Naval brass CuZn36Sn	Cu 62 Zn 37 Sn 1	8.40	915	21.2	26	117	5
Free cutting brass CuZn39Pb3	Cu 58 Zn 39 Pb 3	850	900	20.9	26	109	3,5
Hot stamping brass CuZn40Pb2	Cu 58 Zn 40 Pb 2	8.45	910	20.9	26	109	3,5
High tensile brass	Cu 54–62 Others 7 max. Zinc—balance	8.3–8.4	990 approx.	21 approx.	20–25	88–109	5
Nickel silver 10%	Cu 62 Ni 10 Zn 28	8.60	1010	16.4	8.31	37	8,9
12%	Cu 62 Ni 12 Zn 26	8.64	1025	16.2	7.71	30	8,9
15%	Cu 62 Ni 15 Zn 23	8.69	1060	16.2	7.01	27	8,9
18%	Cu 62 Ni 18 Zn 20	8.72	1100	16.0	6.3	28	8,9
25%	Cu 62 Ni 25 Zn 13	8.82	1160	17.0	5.1	21	8,9

Table 14.5 THE PHYSICAL PROPERTIES OF COPPER AND COPPER ALLOYS AT NORMAL TEMPERATURES—*continued*

Material	*Composition* %	*Density* g cm^{-3}	*Melting point of liquidus* °C	*Coefficient of expansion* 25–300°C 10^{-6} K^{-1}	*Electrical conductivity* 20°C %IACS*	*Thermal conductivity* W m^{-1} K^{-1}	*Refs.*
Phosphor bronze CuSn3P	Sn 3.5 P 0.12	8.85	1 070	18.8	18.8	85	5, 10
CnSn5P	Sn 5 P 0.09	8.85	1 060	18.0	16.8	75	5, 10
CuSn7P	Sn 7 P 0.12	8.80	1 050	18.5	14.0	67	5, 10
CuSn8P	Sn 8 P 0.05	8.80	1 040	18.0	14.0	63	10
Copper-nickel CuNi5Fe	Ni 5.5 Fe 1.2 Mn 0.5	8.94	1 121	17.5	12.5	67	11
CuNi10FeMn	Ni 10.5 Fe 1.5 Mn 0.75	8.94	1 150	17.1	8.0	42	11
CuNi30FeMn	Ni 31.0 Fe 1.0 Mn 1.0	8.90	1 238	16.6	4.5	21	11
Silicon bronze	Si 3 Mn 1	8.52	1 028	18.0	8.1	50	5
Aluminium bronze CuAl5	Cu 95 Al 5	8.15	1 065	18.0	17.7	85	2
CuAl8Fe	Cu 9 Al 8 Fe 2	7.8	1 045	17.0	14.0	0	5
CuAl10Fe5Ni5	Al 9.5 Fe 4.0 Mn 1.0 Ni 5.0	7.57	1 060	17.0	13	62	5

* The International Annealed Copper Standard is material of which the resistance of a wire 1 metre in length and weighing 1 gram is 0.15328 ohm at 20°C. 100% IACS at 20°C = 58.00 MS m^{-1}.
(1) Solution heat treated.
(2) Fully heat treated (to maximum hardness).

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Table 14.6 THE PHYSICAL PROPERTIES OF SOME MAGNESIUM AND MAGNESIUM ALLOYS AT NORMAL TEMPERATURE

Material	*Nominal composition*† %		*Condition*	*Density at 20 °C* g cm^{-3}	*Melting point* °C *Sol.*	*Liq.*	*Coeff. of thermal expansion* 20–200 °C 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm	*Specific heat* 20–200 ° C J kg^{-1} K^{-1}	*Weldability by argon arc process*‡	*Relative damping capacity*§
Pure Mag	Mg	99.97	T1	1.74	650		27.0	167	3.9	1050	A	
Mg–Mn	(MN70)Mn	0.75 approx.	T1	1.75	650	651	26.9	146	5	1050	A	
	(AM503)Mn	1.5	T1	1.76	650	651	26.9	142	5.0	1050	A	C
Mg–Al	AL80Al	0.75 approx.	T1	1.75	630	640	26.5	117	6	1050	A	
	Be	0.005										
Mg–Al–Zn	(AZ31)Al	3	T1	1.78	575	630	26.0	(84)	10.0	1050	A	
	Zn	1										
	(A8)Al	8	AC	1.81	475*	600	27.2	84	13.4	1000	A	C
	Zn	0.5	AC T4	1.81			27.2	84	–	1000		
	(AZ91)Al	9.5	AC	1.83	470*	595	27.0	84	14.1	1000	A	C
	Zn	0.5	AC T4	1.83			27.0	84	–	1000		
			AC T6	1.83			27.0	84	–	1000		
	(AZM)Al	6	T1	1.80	510	610	27.3	79	14.3	14 000	A	
	Zn	1										
	(AZ855)Al	8	T1	1.80	475*	600	27.2	79	14.3	1000	A	
	Zn	0.5										
Mg–Zn–Mn	(ZM21)Zn	2	T1	1.78			27.0			–	A	
	Mn	1										
Mg–Zn–Zr	(ZW1)Zn	1.3	T1	1.80	625	645	27.0	134	5.3	1000	A	A
	Zr	0.6										
	(ZW3)Zn	3	T1	1.80	600	635	27.0	125	5.5	960	C	
	Zr	0.6										
	(Z5Z)Zn	4.5	AC T6	1.81	560	640	27.3	113	6.6	960	C	
	Zr	0.7										
	(ZW6)Zn	5.5	T5	1.83	530	630	26.0	117	6.0	1050	C	
	Zr	0.6										

continued overleaf

Table 14.6 THE PHYSICAL PROPERTIES OF SOME MAGNESIUM AND MAGNESIUM ALLOYS AT NORMAL TEMPERATURE – *continued*

Material	*Nominal composition*† %	*Condition*	*Density at* 20 °C $g\,cm^{-3}$	*Melting point* °C *Sol.*	*Liq.*	*Coeff. of thermal expansion* 20–200 °C $10^{-6}\ K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$	*Electrical resistivity* μΩ cm	*Specific heat* 20–200 °C $J\,kg^{-1}\,K^{-1}$	*Weldability by argon arc process*‡	*Relative damping capacity*§
Mg–Y–RE–Zr	(WE43)Y 4.0 RE(Δ) 3.4 Zr 0.6	AC T6	1.84	550	640	26.7	51	14.8	966	A	
	(WE54)Y 5.1 RE(Δ) 3.0 Zr 0.6	AC T6	1.85	550	640	24.6	52	17.3	960	A	
Mg–RE–Zn–Zr	(ZRE1)RE 2.7 ZN 2.2 Zr 0.7	AC T5	1.80	545	640	26.8	100	7.3	1050	A	B
	(RZ5)Zn 4.0 RE 1.2 Zr 0.7	AC T5	1.84	510	640	27.1	113	6.8	960	B	
	(ZE63)Zn 6 RE 2.5 Zr 0.7	AC T6	1.87	515	630	27.0	109	5.6	960	A	
Mg–Th–Zn–Zr**	(ZTY)Th 0.8 Zn 0.5 Zr 0.6	T1	1.76	600	645	26.4	121	6.3	960	A	

	(ZT1)Th 3.0 Zn 2.2 Zr 0.7	AC T5	1.83	550	647	26.7	105	7.2	960	A	(B)	
	(TZ6)Zn 5.5 Th 1.8 Zr 0.7	AC T5	1.87	500	630	27.6	113	6.6	960	B		
Mg–Ag–RE–Zr	(QE22)Ag 2.5 RE(D) 2.0 Zr 0.6	AC T6	1.82	550	640	26.7	113	6.85	1000	A		
	(EQ21)RE(D) 2.2 Ag 1.5 Cu 0.07 Zr 0.7	AC T6	1.81	540	640	26.6	113	6.85	1000	A		
Mg–Zn–Cu–Mn	(ZC63)Zn 6.0 Cu 2.7 Mn 0.5	AC T6	1.87	465	600	26.0	122	5.4	962	B		
	(ZC71)Zn 6.5 Cu 1.3 Mn 0.8	T6	1.87	465	600	26.0	122	5.4	62	B		
MG–Ag–RE–** Th–Zr	(QH21)Ag 2.5 RE(D) 1.0 Th 1.0 Zr 0.7	AC T6	1.82	540	640	26.7	113	6.85	1005	A	–	
Mg–Zr	(ZA)Zr 0.6	AC	1.75	650	651	27.0	(146)	(4.5)	1050	A	A	

AC Sand cast.
T4 Solution heat treated.

T5 Precipitation heat treated.
T6 Fully heat treated.

† Mg–Al type alloys *normally* contain 0.2–0.4% Mn to improve corrosion resistance.
** Thorium containing alloys are being replaced by alternative Mg alloys.

T1 Extruded, rolled or forged.
RE Cerium mischmetal containing approx. 50% Ce.
* Non-equilibrium solidus 420 °C.
() Estimated value.

RE(D) Mischmetal enriched in neodymium.

RE(Δ) Neodymium + Heavy Rare Earths.

‡ Weldability rating:
A Fully weldable.

B Weldable.
C Not recommended where fusion welding is involved.

§ Damping capacity rating:
A Outstanding.

B Equivalent to cast iron.

C Inferior to cast iron but better than Al-base cast alloys.

14.6 The physical properties of nickel and nickel alloys

Table 14.7 THE PHYSICAL PROPERTIES OF WROUGHT NICKEL AND SOME HIGH NICKEL ALLOYS AT ROOM TEMPERATURE

*Alloy**	*Nominal composition* %	*Density* $g\,cm^{-3}$	*Coefficient of expansion* 20–100°C $10^{-6}K^{-1}$	*Specific heat* $Jkg^{-1}K^{-1}$	*Thermal conductivity* $Wm^{-1}K^{-1}$	*Electrical resistivity* $\mu\Omega cm$
Nickel	99.4 Ni	8.89	13.3	456	74.9	9.5
Nickel 205	99.6 Ni	8.89	13.3	456	75.0	9.5
Monel† alloy 400	30 Cu 1.5 Fe 1.0 Mn	8.83	13.9	423	21.7	51.0
Monel 450	31.0 Ni 0.7 Fe Rem. Cu	8.91	15.5	380	29.4	41.2
Monel alloy K-500	29 Cu 2.8 Al 0.5 Ti	8.46	13.7	419	17.4	61.4
Cupro-nickel	55 Cu	8.88	14.9	421	19.5	52.0
Inconel† alloy 600	16 Cr 6 Fe	8.42	13.3	460	14.8	103
Inconel 601	60.5 Ni 23.0 Cr 1.4 Al 15.1 Fe	8.11	13.75	448	11.2	119
Inconel 617	55.7 Ni 21.5 Cr 12.5 Co 9.0 Mo 1.2 Al 0.1 C	8.36	11.6	419	13.6	122
Inconel alloy 625	22 Cr 4 Nb 9 Mo 0.3 Ti 0.3 Al	8.44	12.8	410	9.8	129
Inconel 718	52.5 Ni 19.0 Cr 18.8 Fe 5.2 Nb 3.1 Mo 0.9 Ti 0.5 Al	8.19	13	435	11.4	125
Inconel alloy X-750	15 Cr 7 Fe 2.5 Ti 0.6 Al 0.8 Nb	825	12.6	425	12.0	122
Inconel MA 754	78.0 Ni 20.0 Cr 1.0 Fe 0.6 Y203	8.3	12.2		14.26	107.5
INCO 330	35.5 Ni 44.8 Fe 18.5 Cr 1.2 Si	8.08	14.9	460	12.4	101.7
INCO 020	35.0 Ni 38.4 Fe 20.0 Cr 3.5 Cu 2.5 Mo 0.6 Nb	8.05	14.7	500	12.3	108

Table 14.7 THE PHYSICAL PROPERTIES OF WROUGHT NICKEL AND SOME HIGH NICKEL ALLOYS AT ROOM TEMPERATURE—*continued*

*Alloy**	*Nominal composition* %	*Density* g cm^{-3}	*Coefficient of expansion* 20–100°C 10^{-6} K^{-1}	*Specific heat* J kg^{-1} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
INCO G-3	49.0 Ni, 22.5 Cr, 19.5 Fe, 7.0 Mo, 2.0 Cu	8.3	12.2		14.26	107.5
INCO C-276	59.0 Ni, 16.0 Mo, 15.5 Cr, 5.5 Fe, 4.0 W	8.89	12.2	427	9.8	122.9
INCO-HX	48.3 Ni, 22.0 Cr, 18.5 Fe, 9.0 Mo, 1.5 Co, 0.6 W, 0.1 C	8.23	13.3	461	11.6	116
Incoloy† alloy 800 Incoloy alloy 800 H‡	45 Fe, 21 Cr, 0.4 Ti, 0.4 Al	7.95	142.	460	11.5	93
Incoloy alloy 825	32 Fe, 21 Cr, 3 Mo, 2 Cu, 1.0 Ti	814	14.0	441	11.1	113
Incoloy alloy DS	40 Fe, 18 Cr, 2 Si	7.91	14.2	450	12.0	108
Ni Span† alloy C-902	47 Fe, 5.5 Cr, 2.5 Ti, 0.5 Al	8.10	7.6	502	12.1	101
Hastelloy B 2	28 Mo	9.22	10.3	373	11.1	137
Hastelloy C 4	16 Mo, 16 Cr	8.64	10.8	406	10.1	125
Hastelloy alloy X	9 Mo, 21 Cr, 18 Fe	8.23	13.8	485	9.1	118
Nimonic† alloy 75	20 Cr, 0.4 Ti	8.37	11.0	461	11.7	102
Nimonic alloy 80A	20 Cr, 2.0 Ti, 1.5 Al	8.19	12.7	460	11.2	117
Nimonic alloy 81	30 Cr, 1.8 Ti, 1.0 Al	8.06	11.1	461	10.9	127
Nimonic alloy 90	20 Cr, 17 Co, 2.4 Ti, 1.4 Al	8.18	12.7	445	11.5	114
Nimonic alloy 105	15 Cr, 20 Co, 5 Mo, 5 Al, 1.2 Ti	8.01	12.2	419	10.9	131
Nimonic alloy 115	14 Cr, 13 Co, 3 Mo, 5 Al, 4 Ti	7.85	12.0	444	10.6	139

Table 14.7 THE PHYSICAL PROPERTIES OF WROUGHT NICKEL AND SOME HIGH NICKEL ALLOYS AT ROOM TEMPERATURE—*continued*

*Alloy**	*Nominal composition* %	*Density* $g\,cm^{-3}$	*Coefficient of expansion* 20–100°C $10^{-6}\,K^{-1}$	*Specific heat* $J\,kg^{-1}\,K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$	*Electrical resistivity* $\mu\Omega\,cm$
Nimonic alloy 263	20 Cr 2 Ti 20 Co 0.5 Al 6 Mo	8.36	11.1	461	11.7	115
Nimonic alloy 901	13 Cr 3 Ti 35 Fe 6 Mo	8.16	13.5	419	—	—
Nimonic alloy PE16	16 Cr 1.0 Ti 32 Fe 1.0 Al 3 Mo	8.02	11.3	544	11.7	110
Nimonic PK33	18.0 Cr 14.0 Co 7.0 Mo 2.25 Ti 2.1 Al	8.21	12.1	419	11.3	126
Astroloy	54.8 Ni 15.0 Cr 17.0 Co 5.3 Mo 4.0 Al 3.5 Ti	7.91				
Rene 41	55.4 Ni 19.0 Cr 11.0 Co 11.0 Mo 1.5 Al 3.1 Ti	8.25			9	130.8
Rene 95	61.5 Ni 14.0 Cr 8.0 Co 3.5 Mo 3.5 Nb 3.5 Al 2.5 Ti				8.7	
Udimet 500	53.7 Ni 18.0 Cr 18.5 Co 4.0 Mo 2.9 Al 2.9 Ti	8.02			11.1	120.3
Udimet 700	55.5 Ni 15.0 Cr 17.0 Co 5.0 Mo 4.0 Al 3.5 Ti	7.91			19.6	
Waspaloy	58.7 Ni 19.5 Cr 13.5 Co 4.3 Mo 1.3 Al 3.0 Ti	8.19			10.7	124

* Where trade marks apply to the name of an alloy there may be materials of similar composition available from other producers who may or may not use the same suffix along with their own trade names. The suffix alone e.g. Alloy 800 is sometimes used as a descriptive term for the type of alloy but trade marks can be used only by the registered user of the mark.

† Registered Trade Mark.

‡ A variant on alloy 800 having controlled carbon and heat treatment to give significantly improved creep-rupture strength.

14.7 The physical properties of titanium and titanium alloys

Table 14.8 PHYSICAL PROPERTIES OF TITANIUM AND TITANIUM ALLOYS AT NORMAL TEMPERATURES

Material IMI designation	*Nominal composition %*	*Density* $g\,cm^{-3}$	*Coefficient of expansion* 20–100 °C $10^{-6}\,K^{-1}$	*Thermal conductivity* 20–100 °C $W\,m^{-1}\,K^{-1}$	*Resistivity* 20 °C $\mu\Omega\,cm$	*Temp. coefficient of resistivity* 20–100 °C $\mu\Omega\,cm\,K^{-1}$	*Specific heat* 50 °C $J\,kg^{-1}\,K^{-1}$	*Magnetic suscept.* 10^{-6} cgs *units* g^{-1}
CP Titanium	Commercially pure	4.51	7.6	16	48.2	0.0022	528	+3.4
IMI 230	Cu 2.5	4.56	9.0	13	70	0.0026	–	–
IMI 260/261	Pd 0.2	4.52	7.6	16	48.2	0.0022	528	–
IMI 315	Al 2.0 Mn 2.0	4.51	6.7	8.4	101.5	0.0003	460	+4.1
IMI 317	Al 5.0 Sn 2.5	4.46	7.9	6.3	163	0.0006	470	+3.2
IMI 318	Al 6.0 V 4.0	4.42	8.0	5.8	168	0.0004	610	+3.3
IMI 550	Al 4.0 Mo 4.0 Sn 2.0 Si 0.5	4.60	8.8	7.9	159	0.0004	–	–
IMI 551	Al 4.0 Mo 4.0 Sn 4.0 Si 0.5	4.62	8.4	5.7	170	0.0003	400	+3.1
IMI 679	Sn 11.0 Zr 5.0 Al 2.25 Mo 1.0 Si 0.2	4.84	8.0	7.1	163	0.0004	–	–
IMI 680	Sn 11.0 Mo 4.0 Al 2.25 Si 0.2	4.86	8.9	7.5	165	0.0003	–	–
IMI 685	Al 6.0 Zr 5.0 Mo 0.5 Si 0.25	4.45	9.8	4.8	167	0.0004	–	–
IMI 829	Al 5.5 Sn 3.5 Zr 3.0 Nb 1.0 Mo 0.3 Si 0.3	4.53	9.45	7.8	–	–	530	–
IMI 834	Al 5.8 Sn 4.0 Zr 3.5 Nb 0.7 Mo 0.5 Si 0.35 C 0.06	4.55	10.6	–	–	–	–	–

14.8 The physical properties of zinc and zinc alloys

Table 14.9 PHYSICAL PROPERTIES OF ZINC AND ZINC ALLOYS

Material	*Nominal composition*	*Density* $g\,cm^{-3}$	*Coefficient of expansion* $10^{-6}\,K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$	*Electrical conductivity* %IACS 20°C	*Condition*	*Melting point (liquidus)* °C
Zn Polycrystalline	99.993% Zn	7.13 (25°C)	39.7 (20–250°C)	113	28.27	Cast	419.46
ZnAlMg BS1004A	4% Al 0.04% Mg	6.7	27 (20–100°C)	113	27	Pressure die cast	387
ZnAlCuMg BS1004B	4% Al 1% Cu 0.04% Mg	6.7	27 (20–100°C)	109	26	Pressure die cast	388
ZnAlCuMg ILZRO 12 (ZA12)	11% Al 1% Cu 0.02% Mg	6.0	28 (20–100°C)	115	28.3	Chill cast	432
ZA27	27% Al 2.3% Cu 0.015% Mg	5.0	26 (20–100°C)	123	29.7	Chill cast	487

14.9 The physical properties of zirconium alloys

Table 14.10 PHYSICAL PROPERTIES OF ZIRCONIUM ALLOY

Alloy	*Composition* %	*Density* $g\,cm^{-3}$	*Thermal cond. at 25°C* $W\,m^{-1}\,K^{-1}$	*Coefficient of expansion 20–100°C* 10^{-6}	*Electrical resistivity* $\mu\Omega\,cm$
Zirconium 10	Commercially pure	6.50	21.1	5.04	—
Zirconium 30	Cu 0.55 Mo 0.55	6.55	25.3	5.93	—
Zircalloy II	Sn 1.5 Fe 0.12 Cr 0.10 Ni 0.05	6.55	12.3	5.67	—
Zr 702	Commercially pure with up to 4.5 Hf	6.51	22	5.89	39.7
Zr 704	Cr+Fe 0.2–0.4 Sn 1–2	6.57	—	—	—
Zr 705	Nb 2.5 O_2 0.18	6.64	17.1	6.3	55
Zr 706	Nb 2.5 O_2 0.16	6.64	17.1	6.3	55

See also Table 26.36 page 26–52.

14.10. The physical properties of pure tin

Melting point		231.9°C
Boiling point		2270°C
Vapour pressure at	727°C	7.4×10^{-6} mm Hg
	1127°C	4.4×10^{-2} mm Hg
	1527°C	5.6 mm Hg
Volume change of freezing		2.7%
Expansion on melting		2.3%
Phase transformation	$\alpha \rightleftarrows \beta$	13.2°C
Density at 20°C		$7.28\,g/cm^3$
Specific heat at 20°C		$222\,J\,kg^{-1}\,K^{-1}$

Latent heat of fusion	$59.6\,kJ\,kg^{-1}$
Latent heat of evaporation	$2497\,J\,kg^{-1}$
Linear expansion coefficient at 0–100°C	$23.5 \times 10^{-6}\,K^{-1}$
Thermal conductivity at 0–100°C	$66.8\,W\,m^{-1}\,K^{-1}$
Electrical conductivity at 20°C	15.6 IACS
Electrical restivity at 20°C	$12.6\,\mu\Omega\,cm$
Temperature coefficient of electrical resistivity at 0–100°C	$0.0046\,K^{-1}$
Thermal EMF against platinum	
cold junction at 0°C	
hot junction at 100°C	+0.42 mV
Superconductivity, critical temperature (T_c)	3.722 K
Viscosity	0.01382 poise at 351°C
	0.01148 poise at 493°C
Surface tension	$548\,mN\,m^{-1}$ at 260°C
	$529\,nM\,m^{-1}$ at 500°C
Gas solubility in liquid tin:	
Oxygen at 536°C	0.00018%
Oxygen at 750°C	0.0049%
Hydrogen at 1000°C	0.04%
Hydrogen at 1300°C	0.36%
Nitrogen	Very low

14.11 The physical properties of steels

Table 14.11 PHYSICAL PROPERTIES OF STEELS

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* $g\,cm^{-3}$	*Thermal properties (see Notes)* *Specific heat* $J\,kg^{-1}\,K^{-1}$	*Coefficient of thermal expansion* $10^{-6}\,K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$	*Electrical resistivity* $\mu\Omega\,cm$
Carbon steels						
C 0.06, Mn 0.4	RT	7.87	—	—	65.3	12.0
	100		48.2	12.62	60.3	17.8
	200		520	13.08	54.9	25.2
Annealed	400		595	13.83	45.2	44.8
	600		754	14.65	36.4	72.5
	800		875	14.72	28.5	107.3
	1000		—	13.79	27.6	116.0
C 0.08, Mn 0.31	RT	7.86	—	—	59.5	13.2
	100		482	12.19	57.8	19.0
	200		523	12.99	53.2	26.3
Annealed	400		595	13.91	45.6	45.8
	600		741	14.68	36.8	73.4
	800		960	14.79	28.5	108.1
	1000		—	13.49	27.6	116.5
C 0.23, Mn 0.6 En 3 / 060A22	RT	7.86	—	—	51.9	15.9
	100		486	12.18	51.1	21.9
	200		520	12.66	49.0	29.2
Annealed	400		599	13.47	42.7	48.7
	600		749	14.41	35.6	75.8
	800		950	12.64	26.0	109.4
	1000		—	13.37	27.2	116.7

Notes:

1. Where *specific heats* are quoted at temperatures above RT the values have been determined over a range of 50 C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition Composition %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)*			*Electrical resistivity* μΩ cm
			Specific heat J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	
C 0.42 } En 8 Mn 0.64 } 060A42	RT	7.85	—	—	51.9	16.0
	100		486	11.21	50.7	22.1
	200		515	12.14	48.2	29.6
Annealed	400		586	13.58	41.9	49.3
	600		708	14.58	33.9	76.6
	800		624	11.84	24.7	111.1
	1 000		—	13.59	26.8	122.6
C 0.80 } Mn 0.32 }	RT	7.85	—	—	47.8	17.0
	100		490	11.11	48.2	23.2
	200		532	11.72	45.2	30.8
Annealed	400		607	13.15	38.1	50.5
	600		712	14.16	32.7	77.2
	800		616	13.83	24.3	112.9
	1 000		—	15.72	26.8	119.1
C 1.22 } Mn 0.35 }	RT	7.83	—	—	45.2	18.4
	100		486	10.6	44.8	25.2
	200		540	11.25	43.5	33.3
Annealed	400		599	12.88	38.5	54.0
	600		699	14.16	33.5	80.2
	800		649	14.33	23.9	115.2
	1 000		—	16.84	26.0	122.6
C 0.23 } En 14 Mn 1.51 } 150M19	RT	7.85	—	—	46.1	19.7
	100		477	11.89	46.1	25.9
	200		511	12.68	44.8	33.3
Annealed	400		590	13.87	39.8	52.3
	600		741	14.72	34.3	78.6
	800		821	12.11	26.4	110.3
	1 000		—	13.67	27.2	117.4
C 0.13 } Mn 0.61 } Ni 0.12 }	0	7.84	435			16.3
	100		494			22.6
	200		528			29.6
	400		599			48.2
Annealed	600		754			74.2
	800		833			110.0
	1 000		657			119.4
Low alloy steels						
C 0.40 } 1% Ni Mn 0.67 } En 12 Ni 0.80 }	RT	7.85	*—	—	—	21.9
	100		486	11.90	49.4	26.4
	200		507	12.55	46.9	33.4
Hardened 850 °C OQ	400		544	13.75	40.6	52.0
Tempered 600 °C (1h) OQ	600		586	14.45	34.8	77.5
C 0.37 } Mn–Mo Mn 1.56 } En 16 Mo 0.26 } 605A37	RT	7.85	*—	—	—	25.4
	100		456	12.45	48.2	30.6
	200		477	13.20	45.6	39.1
Hardened 845 °C OQ	400		532	14.15	39.4	60.0
Tempered 600 °C (1h)	600		599	14.80	33.9	88.5

Notes:

* Where a group is marked with an asterisk the Values are a mean from RT up to the temperature quoted.

1. Where *specific heats* are quoted at temperatures above RT the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.37 Mn 1.48 Mo 0.43 Mn–Mo En 17 608M38	RT	7.85	*—	—	—	22.5
	100		482	12.45	45.6	27.2
	200		494	13.00	44.0	34.3
Hardened 850 °C OQ	400		519	13.90	39.4	52.5
Tempered 620 °C (1h) OQ	600		595	14.75	33.9	77.5
C 0.32 Mn 0.69 Cr 1.09 1%Cr En 18B 530A32	RT	7.84	—	—	48.6	20.0
	100		494	12.16	46.5	25.9
	200		523	12.83	44.4	33.0
Annealed	400		595	13.72	38.5	51.7
	600		741	14.46	31.8	77.8
	800		934	12.13	26.0	110.6
	1000		—	13.66	28.1	117.7
C 0.39 Mn 0.79 Cr 1.03 1% Cr En 18D 530A40	RT	7.85	*—	—	—	22.8
	100		452	12.35	44.8	28.1
	200		473	13.05	43.5	35.2
Hardened 850 °C OQ	400		519	14.40	37.7	53.0
Tempered 640 °C (1h) OQ	600		561	15.70	31.4	78.5
C 0.28/0.33 Mn 0.4/0.6 Si 0.2/0.35 Cr 0.8/1.1 Mo 0.15/0.25 1% Cr–Mo	0		—		42.7	—
	RT	7.85	—		—	22.3
	100		477		42.7	27.1
	200		515		—	34.2
	300		544		40.6	—
Hardened and tempered	400		595		—	52.9
	500		657		37.3	—
	600		737		—	78.6
	700		825		31.0	—
	800		883		—	110.3
	1000		—		28.1	117.1
	1200		—		30.1	122.2
C 0.41 Mn 0.67 Cr 1.01 Mo 0.23 1% Cr–Mo En 19 708A42	RT	7.83	*—	—	—	22.2
	100		—	12.25	42.7	26.3
	200		473	12.70	42.3	32.6
	400		519	13.70	37.7	47.5
Hardened 850 °C OQ	600		561	14.45	33.1	64.6
Tempered 600 °C (1h) OQ						
C 0.4 Mn 0.4 Cr 1.1 Mo 0.7 1% Cr–Mo En 20B	RT	7.85		—	—	—
	100			12.3	41.9	
	200			12.6	41.9	
	400			13.7	38.9	
Hardened and tempered	600			14.4	32.7	
	800			—	26.0	
C 0.4 Mn 0.6 Cr 3.0 Mo 0.8 V 0.2 3% Cr–Mo–V En 40C 897M39	RT	7.83		—	—	—
	100			12.5	37.7	
	200			12.9	37.7	
	400			13.5	34.8	
Hardened and tempered	600			14.0	31.0	

Notes:

* The values are a mean from RT up to the temperature quoted.

1. Where *specific heats* are quoted at temperatures above RT the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)*			
			Specific heat J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.35, Mn 0.59, Ni 0.20, Cr 0.88, Mo 0.20 — Low Ni–Cr–Mo En 19	RT	7.84	—	—	42.7	21.1
	100		477	12.67	42.7	27.1
	200		515	13.11	41.9	34.2
	400		595	13.82	38.9	52.9
	600		737	14.55	33.9	78.6
Annealed	800		883	11.92	26.4	110.3
	1000		—	13.86	28.1	117.1
C 0.23, Mn 0.45, Si 0.45, Cr 2.87, W 0.59, Mo 0.51, V 0.77 — 3% Cr–W–Mo–V	RT	7.83		—	38.5	35.5
	100			11.9	33.6	39.0
	200			12.4	33.1	46.2
	400			13.1	30.6	63.0
	600			13.6	29.3	85.4
	800			14.1	28.9	—
Hardened and tempered						
C 0.32, Mn 0.55, Ni 3.47 — 3½% Ni En 21	RT	7.85	—	—	36.4	25.9
	100		482	11.20	37.7	32.0
	200		523	11.80	38.9	39.0
Annealed	400		590	12.90	36.8	56.7
	600		749	13.87	32.7	81.4
	800		604	11.10	25.1	112.2
	1000		—	13.29	27.6	118.0
C 0.33, Mn 0.50, Ni 3.4, Cr 0.8 — 3% Ni–Cr En 23	RT	7.85	—	—	34.3	25.6
	100		494	11.36	36.0	31.7
	200		523	12.29	36.8	38.7
	400		599	13.18	36.4	56.7
Hardened and	600		775	13.72	31.8	81.7
tempered	800		557	10.69	26.0	111.5
	1000		—	13.11	27.6	117.8
C 0.41, Ni 1.43, Cr 1.07, Mo 0.26 — 1½% Ni–Cr–Mo En 24 817M40	RT	7.84		—		24.8
	100			—		29.8
	200			12.40		36.7
	400			13.60		55.2
Hardened 830°C OQ	600			14.30		79.7
Tempered 630°C (1h) OQ						
C 0.32, Ni 2.60, Cr 0.67, Mo 0.51 — 2½% Ni–Cr–Mo En 25 826M31	RT	7.85		—		27.7
	100			—		32.1
	200			11.55		38.7
	400			13.10		57.3
Hardened 830°C OQ	600			13.85		82.5
Tempered 650°C OQ						
C 0.34, Mn 0.54, Ni 3.53, Cr 0.76, Mo 0.39 — 3% Ni–Cr–Mo En 27	RT	7.86	—	—	33.1	27.7
	100		486	11.63	33.9	33.7
	200		523	12.12	35.2	40.6
	400		607	13.12	35.6	58.2
	600		770	13.79	30.6	82.5
Hardened and tempered	800		636	10.67	26.8	111.4
	1000		—	12.96	28.5	117.6

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50°C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)*			*Electrical resistivity* μΩ cm
			Specific heat J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	
C 0.29, Ni 4.23, Cr 1.26 — 4¼% Ni–Cr, En 30A, 665A17	RT	7.83		—	—	37.0
	100			10.55	27.6	41.6
	200			12.00	29.7	49.3
Hardened 820 °C AC, Tempered 250 °C (1h)						
C 0.18, Ni 1.76, Mo 0.20 — 2% Ni–Mo, En 34, 665A17	RT	7.85		—		24.9
	100			12.50		29.6
	200			13.10		37.1
Blank carburized 920 °C, Hardened 800 °C OQ						
C 0.15, Ni 4.25, Cr 1.18, Mo 0.20 — 4¼% Ni–Cr–Mo, En 39B, 835A15	RT	7.85		—		36.3
	100			11.30		40.1
	200			12.55		46.7
Blank carburized 920 °C, Hardened 800 °C OQ						
C 0.39, Mn 1.35, Ni 0.65, Cr 0.48, Mo 0.17 — Low alloy steel, En 100, 945M38	RT	7.86		—		24.7
	100			12.00		28.2
	200			12.75		34.0
	400			14.00		52.0
	600			14.75		74.7
Hardened 850 °C OQ, Tempered 620 °C (1h) OQ						
C 0.39, Ni 1.39, Cr 1.02, Mo 0.14 — Low Ni–Cr–Mo, En 110, 816M40	RT	7.84		—		24.8
	100			12.00		29.2
	200			12.65		35.6
	400			13.65		54.0
	600			14.30		78.0
Hardened 840 °C OQ, Tempered 650 °C (1h) OQ						
C 0.17, Ni 0.86, Cr 0.71 — ¼% Ni–Cr, En 351, 635A14	RT	7.85		—		29.1
	100			12.80		34.2
	200			13.10		41.1
Blank carburized 910 °C, Hardened 820 °C OQ						
C 0.17, Ni 1.25, Cr 1.02, Mo 0.15 — 1¼% Ni–Cr–Mo, En 353, 815A16	RT	7.87		—		31.8
	100			11.30		36.6
	200			12.45		43.2
Blank carburized 910 °C, Hardened 810 °C OQ						
C 0.16, Ni 2.00, Cr 1.50, Mo 0.20 — 2% Ni–Cr–Mo, En 355, 822A17	RT	7.84		—		34.5
	100			11.80		39.2
	200			12.30		45.7
Blank carburized 910 °C, Hardened 810 °C OQ						

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.48, Mn 0.90, Si 1.98, Cu 0.64 — 2% Si–Cu	RT	7.73	—	—	25.1	41.9
Annealed	100		498	11.19	28.5	47.0
	200		523	12.21	30.1	52.9
	400		603	13.35		68.5
	600		749	14.09		91.1
	800		528	13.59		117.3
	1 000		—	14.54		122.3
C 0.05, Mn 0.3, Si 0.7, B 1.96, Al 0.03 — 2% B	0			—		24.9
Hot worked	RT	7.72	461	—		—
	100			10.0		30.9
	200			11.0		38.7
	400			11.9		57.4
	600			11.8		81.9
	800			13.3		—
C 0.10, Mn 0.14, Si 0.43, B 4.2, Al 0.53 — 4% B	0			—		39.9
As cast	RT	7.40	523	—		—
	100			9.5		50.6
	200			—		61.5
	300			10.4		72.3
	400			—		83.3
	500			11.2		—
	600			—		106.5
	700			11.8		—
	800			—		129.4
	1 000			13.0		—
Typically						
C 0.10, Mo 0.5, B 0.004 — ½% Mo–B 'Fortiweld'	RT	7.86	*440	12.00	46.1	20.0
Normalized and stress-relieved 600 °C	100		465	12.55	45.2	24.5
	200		494	13.25	44.4	31.0
	400		557	14.30	41.5	48.5
	600		632	15.10	36.9	74.5
	700		674	15.40	35.2	88.0
C 0.10, Si 1.0 max, Cr 4.0/6.0 — 5% Cr AISI 502	30	7.7		—	36.0	
Annealed	100			11.0	—	
	200			11.6	35.2	
	400			12.6	—	
	600			13.3	—	
	800			—	26.8	
	1 200			—	26.8	
High alloy steels						
C 0.45, Mn 0.5, Si 3.5, Cr 3.5 — 3% Cr–3% Si	RT	7.6		—	22.2	80
Hardened and tempered	100			13.0	—	
	300			13.0	—	
	500			13.0	—	
	700			14.0	—	
	900			—	31.4	

Notes:

* The values are a mean from RT up to the temperature quoted.

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition Composition %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.45, Mn 0.5, Cr 8.0, Si 3.4 — 8% Cr–3% Si, En 52, 401S45	RT	7.6		—	22.2	80.0
Hardened and tempered	100			13.0	—	—
	300			13.0	—	110.0
	500			13.0	—	
	700			14.0	—	
	900			—	31.4	
C 0.40, Mn 0.3, Cr 11.5 — 11% Cr	RT	7.75		—	23.5	60.0
Hardened and tempered	100			10.0	—	—
	300			11.0	—	—
	500			12.0	—	—
	700			12.0	—	—
	750			—	24.3	119.0
C 0.12, Cr 9.0, Mo 1.0 — 9% Cr–Mo	RT	7.78	*402	11.15	26.0	49.9
Normalized and tempered	100		427	11.30	26.4	55.5
	200		461	11.60	26.8	63.0
	400		528	12.10	27.6	79.5
	600		595	12.65	26.8	97.5
	700		624	12.85	26.8	106.5
C 0.20, Mn 0.4, Cr 11.0, Mo 0.5, V 0.7, Nb 0.15 — 11% Cr–Mo–V–Nb	RT	7.75		—		
Hardened and tempered	100			9.3		
	200			10.9		
	400			11.5		
	600			12.1		
	800			12.2		
C 0.13, Mn 0.25, Cr 12.95, Ni 0.14 — 13% Cr, En 56B, 420S29	RT	7.74	—	—	26.8	48.6
Annealed	100		473	10.13	27.6	58.4
	200		515	10.66	27.6	67.9
	400		607	11.54	27.6	85.4
	600		779	12.15	26.4	102.1
	800		691	12.56	25.1	116.0
	1000		—	11.70	27.6	117.0
C 0.07, Mn 0.8, Cr 17.0 — 17% Cr	RT	7.7		—	21.8	62.0
Annealed	100			10.0		
	200			11.0		
	300			12.0		
C 0.06, Mn 0.8, Cr 21.0 — 21% Cr	RT	7.76	482	—	21.8	62.0
Annealed	100			10.0		
	300			11.0		
	500			11.0		
	700			12.0		
	900			13.0		
C 0.22, Cr 30.4, Ni 0.26 — 30% Cr–Ni	RT	7.90		—	12.6	80.0
Hardened and tempered	100			10.0		

Notes:

* The values are a mean from RT up to the temperature quoted.

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT, up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 1.22, Mn 13.0 — 13% Mn	RT	7.87	—	—	13.0	66.5
1050°C Air-cooled	100		519	18.01	14.6	75.7
	200		565	19.37	16.3	84.7
	400		607	21.71	19.3	100.4
	600		704	19.86	21.8	110.0
	800		649	21.86	23.5	120.4
	1000		673	23.13	25.5	127.5
C 0.28, Mn 0.89, Ni 28.4 — 28% Ni	RT	8.16	—	—	12.6	82.9
950°C, WQ	100		502	13.73	14.7	89.1
	200		519	15.28	16.3	94.7
	400		540	17.02	18.9	103.9
	600		586	17.82	22.2	111.2
	800		586	18.28	25.1	116.5
	1000		599	18.83	27.6	120.6
C 0.10, Mn 0.60, Cr 12.0, Al 4.5 — 12% Cr–4% Al AISI 406	RT	7.42	502	—	—	122
Softened	100			11.0	25.1	125
	300			12.0	—	129
	500			12.0	28.5	—
	600			—	—	136
	700			13.0		—
	850			—		141
C 0.72, Mn 0.25, Ni 0.07, Cr 4.26, W 18.5 — 4% Cr–18% W	RT	8.69	—	—	24.3	40.6
Annealed 830°C	100		410	11.23	26.0	47.2
	200		435	11.71	27.2	54.4
	400		502	12.20	28.5	71.8
	600		599	12.62	27.2	92.2
	800		716	12.97	26.0	115.2
	1000		—	12.44	27.6	120.9
C 0.16, Mn 0.2, Ni 2.5, Cr 16.5 — 16% Cr–Ni En 57 431S29	RT	7.7	—	—	18.8	72.0
Softened	100		482	10	—	—
	300			11	—	—
	500			12	24.3	103.0
C 0.08, Mn 0.3/0.5, Ni 8, Cr 18/20 — 18% Cr–8% Ni En 58A 302S25	RT	7.92	—	—	15.9	69.4
1100°C WQ	100		511	14.82	16.3	77.6
	200		532	16.47	17.2	85.0
	400		569	17.61	20.1	97.6
	600		649	18.43	23.9	107.2
	800		641	19.03	26.8	114.1
	1000		—	—	28.1	119.6
C 0.12, Mn 1.5, Ni 11.0, Cr 17.5, Nb 1.2 — 18% Cr–11% Ni (Nb stabilized) En 58G 347S17	RT	7.9		—	15.9	72
Softened	100			16.0	—	
	300			18.0	17.2	
	500			18.0	18.8	
	700			19.0	20.1	

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT, up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %		*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)*			*Electrical resistivity* μΩcm
				Specific heat J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	
C 0.22 Mn 0.6 Cr 20.0 Ni 8.5 Ti 1.2	20% Cr–8% Ni (Ti stabilized)	RT	7.72		—		82
		100			15.0		
		300			15.0		
		500			16.0		
		700			17.0		
Softened		900			18.0		
C 0.15 Mn 0.8 Ni 14 Cr 19 Nb 1.7	19% Cr–14% Ni (Nb stabilized)	RT	7.92		—	—	
		100			17.0	15.1	
		200			17.2	16.8	
		400			17.6	20.1	
		600			18.6	24.3	
Softened							
C 0.30 Mn 0.6 Si 1.5 Ni 8 Cr 20 W 4	18% Cr–8% Ni–W En 55	RT	7.8			13	85
		100			16.0		
		300			17.0		
		500			17.0		
		700			18.0		
		900			18.0		
Softened		1050			—	29	125
C 0.12 Mn 0.3 Ni 8.5 Cr 18.5 Ti 0.8 Al 1.4	18% Cr–8% Ni–Al (Ti stabilized)	RT	7.67		—	18.0	85
		100			15		
		300			15		
		500			15		
		700			16		
		900			17	26.0	125
Normalized and tempered							
C 0.10 Mn 0.3 Ni 12.5 Cr 12.5	12% Cr–12% Ni En 58D	RT	8.01	490	—	15.5	70
		100			18	16.8	77
Softened							
C 0.10 Mn 6.0 Cr 15.0 Ni 10.0 Mo 1.0	15/10/6/1 Cr–Ni–Mn–Mo	RT	7.94	*477	14.80	12.6	74.1
		100		494	15.70	13.8	80.0
		200		511	16.75	15.4	86.7
		400		536	18.25	18.8	99.4
		600		557	18.95	21.8	108.4
Solution treated 1 100 °C		700		565	19.30	23.0	114.4
C 0.27 Mn 1.25 Ni 36 Cr 11	11% Cr–36% Ni	RT	8.08		—	12.1	97
		100			14	—	—
		300			15	—	—
		500			16	18.4	117
Softened							
C 0.1 Mn 1.3 Si 1.2 Ni 1.8 Cr 29.0	30% Cr–Ni	RT	7.5		10	15.9	88
		200			11		
		800			13		
		1000			13		
		1100				26.4	126
Softened							

Notes:

* The values are a mean from RT up to the temperature quoted.

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.1 Mn 1.0 Ni 63 Cr 14 14% Cr–63% Ni Softened	RT	8.1			12.6	105
	100			12.0		
	200			12.5		
	400			13.5		
	600			14.5		
	800			15.5		
	1000			16.5	28.9	110
C 0.30 Mn 3.0 Ni 17.5 Cr 16.5 Mo 3.0 Nb 2.5 Co 7.0 17% Cr–17% Ni–Mo–Co–Nb Softened	RT	8.0		—	12.6	93.8
	100			15		
	300			16		
	500			16		
	700			17		
C 0.4 Mn 0.9 Si 1.4 Ni 13.0 Cr 13.0 W 2.3 Nb 0.9 13% Cr–13% Ni–W–Nb Normalized	RT	8.03		—		
	100			16.8		
	200			17.3		
	400			18.3		
	600			18.9		
	800			19.3		
C 0.4 Mn 0.8 Si 1.0 Ni 13 Cr 13 W 2.5 Mo 2.0 Nb 3.0 Co 10.0 13% Cr–13% Ni–W–Mo–Co–Nb Solution treated	RT	8.13		—	—	
	100			15.6	13.4	
	200			15.8	17.2	
	400			16.9	18.8	
	600			17.3	22.2	
	800			18.0	25.5	
C 0.27 Mn 0.77 Ni 10.5 Cr 19.1 Mo 2.2 Nb 1.4 V 3.0 Co 46.6 20% Cr–10% Ni–46% Co Solution treated and aged	RT	8.26		—	—	
	100			14.8	14.7	
	200			15.0	16.3	
	400			15.2	19.7	
	600			15.9	23.0	
	800			16.8	26.0	
Cast steels						
C 0.11 Mn 0.35 Plain carbon B.S. 1617A A 950 °C, N 950 °C	100			12.2	48.6	19.5
	200			12.6		
	300			13.2		
	400			13.6		
	500			13.9		
	600			14.2		

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.4, Mn 0.5 — Plain carbon BS 1760 A 900 °C, OQ 830 °C T 650 °C	100			11.8	42.3	23.5
	200			12.4		
	300			12.8		
	400			13.3		
	500			13.7		
	600			14.2		
C 0.17, Mn 0.74, Mo 0.50 — Carbon Mo BS 1398 A 920 °C, SR 650 °C	100			12.4		24.2
	200			12.8		
	300			13.1		
	400			13.4		
	500			13.8		
	600			14.2		
C 0.25, Mn 1.55 — 1½% Mn BS 1456 A A 950 °C, WQ 910 °C, T 660 °C	100			13.2		
	200			13.3		
	300			13.7		
	400			14.1		
	500			14.7		
	600			15.2		
C 0.29, Cr 1.80, Ni 0.46, Mo 0.52 — 1½% Cr Ni Mo BS 1458 OQ 900 °C, T 660 °C	100			12.5		27.6
	200			12.7		
	300			13.0		
	400			13.4		
	500			13.9		
	600			14.4		
C 0.34, Ni 2.82, Cr 0.74, Mo 0.42 — 2½% Ni Cr Mo BS 1459 OQ 850 °C, T 640 °C	100			12.0	39.4	27.3
	200			12.3		
	300			12.6		
	400			13.0		
	500			13.5		
	600			13.9		
C 0.24, Cr 3.23, Mo 0.51 — 3% Cr Mo BS 1461 OQ 900 °C, T 690 °C	100			12.2		
	200			12.4		
	300			12.7		
	400			12.9		
	500			13.3		
	600			13.6		
C 0.1, Cr 4.06, Mo 0.57 — 5% Cr Mo BS 1462 N 950 °C, T 680 °C	100			11.8		37.1
	200			12.0		
	300			12.3		
	400			12.5		
	500			12.7		
	600			13.0		
C 0.13, Cr 8.29, Mo 1.1, Si 1.1 — 9% Cr Mo BS 1463 OQ 900 °C, T 690 °C	100			11.9		
	200			11.6		
	300			11.7		
	400			11.7		
	500			11.8		
	600			11.9		

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.27, Cr 12.1, Ni 1.07, Si 1.16 — 13% Cr BS 1630 OQ 930 °C, T 730 °C	100			11.5		
	200			11.8		
	300			12.4		
	400			12.6	25.1	
	500			12.7		
	600			12.9		
C 0.47, Cr 0.85 — Carbon Cr BS 1956 A N 870 °C, T 635 °C	100			12.5		
	200			12.9		
	300			13.2		
	400			13.4		
	500			13.5		
	600			13.6		
C 0.1, Ni 3.35 — 3½% Ni BS 1504–503 WQ 880 °C, T 650 °C	100			11.3		
	200			11.9		
	300			12.2		
	400			12.7		
	500			13.5		
	600			13.6		
C 0.19, Cr 1.13, Mo 0.5 — 1¼% Cr Mo BS 1504–621 N 920 °C, T 625 °C	100			11.8		28.7
	200			12.4		
	300			12.6		
	400			13.3		
	500			13.7		
	600			13.9		
Cast corrosion-resisting steels						
C 0.13, Mn 0.80, Cr 12.5 — 13% Cr BS 1630 A Hardened and tempered	100	7.73	482	11.0	24.7	56
	300			11.0	—	
	500			12.0	—	
	600				27.6	
C 0.25, Mn 0.70, Cr 12.5 — 13% Cr BS 1630 C Hardened and tempered	100	7.75	482	11.0	24.3	57
	300			11.0	—	
	500			12.0	—	
	600			—	26.0	
C 0.07, Si 0.70, Mn 0.80, Ni 8.5, Cr 18.0 — 18% Cr–8% Ni BS 1631 A Normalised	100	7.93	502	17.0	16.3	72
C 0.08, Si 1.00, Mn 0.50, Ni 9.00, Cr 18.0, Nb 0.9 — 18% Cr, 8% Ni Nb BS 1631 B Nb Normalised	100	7.93	502	17.0	15.9	
	300			18.0	—	
	500			18.0	—	
	700			19.0	20.1	

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT, up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)* *Specific heat* J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	*Electrical resistivity* μΩ cm
C 0.12 Si 1.50 Mn 0.80 Ni 9.00 Cr 19.00 Ti 0.6 18% Cr, 8% Ni Ti BS 1631 B Ti Normalised	100	7.78	444	17.0	15.5	70
C 0.06 Si 0.70 Mn 0.70 Ni 12.0 Cr 19.0 Mo 3.6 19% Cr, 12% Ni, 3½% Mo BS 1632 A Water quenched	RT 100	7.96	502	— 16.0	16.3	
C 0.07 Si 1.00 Mn 1.00 Ni 10.5 Cr 18.0 Mo 2.75 18% Cr, 10% Ni 2½% Mo BS 1632 B Normalised	RT 100 200 400 500 600 800	7.96	502	— 16.5 16.9 17.2 17.4 17.9 19.0	16.3	73
C 0.08 Si 1.00 Mn 0.50 Ni 10.5 Cr 18.0 Mo 2.75 Nb 0.90 18% Cr, 10% Ni, 2½% Mo Nb BS 1632 C Nb Normalised	RT 100	7.96	502	— 16.0	16.3 17.6	73
C 0.10 Si 1.50 Mn 0.80 Ni 10.0 Cr 18.0 Mo 2.75 Ti 0.60 18% Cr, 10% Ni, 2½% Mo Ti BS 1632 C Ti Normalised	RT 100	7.78	448	— 17.0	15.5	78
C 0.06 Si 0.70 Mn 0.60 Ni 8.5 Cr 18.0 Mo 2.5 18% Cr, 8% Ni, 2½% Mo BS 1632 D Normalised	RT 100	7.93	502	— 16.0	16.3	
Cast heat-resisting steels						
C 0.25 Si 0.70 Mn 0.70 Cr 12.5 13% Cr BS 1648 A Hardened and tempered	RT 100 300 500 600	7.75	482	— 11.0 11.0 12.0 —	24.3 — — — 26.0	57

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50°C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT, up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)*			*Electrical resistivity* μΩ cm
			Specific heat J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	
C 0.40 Si 0.80 Mn 0.90 Cr 29.0 27% Cr BS 1648 B Tempered	RT	7.63	482	—	20.9	70
	100			10.2		
	200			10.8		
	400			11.0		
	600			11.5		
	800			12.4		
	1 000			13.3		
C 1.70 Si 0.70 Mn 0.70 Cr 27.0 27% Cr BS 1648 C Tempered	RT	7.63	482	—	20.9	70
	100			10.2		
	200			10.8		
	400			11.0		
	600			11.5		
	800			12.4		
	1 000			13.3		
C 0.30 Si 1.50 Mn 1.50 Ni 10.0 Cr 20.0 20% Cr 10% Ni BS 1648 D	RT	7.74	502	—	—	80
	100			—	15.5	
	500			17.8	—	
	800			18.5	26.8	
	1 100			19.6	—	
C 0.35 Si 1.50 Mn 0.80 Ni 7.0 Cr 21.0 W 4.0 21% Cr 8% Ni 4% W BS 1648 D	RT	7.92	435	—	10.9	86
	100			13.6		
	300			14.5		
	500			15.4		
	700			16.5		
	900			17.7	26.8	
	1 000			18.3	—	
C 0.20 Si 1.20 Mn 1.30 Ni 13.0 Cr 25.0 25% Cr 12% Ni BS 1648 E Normalised	RT	7.92	544	—	13.8	85
	100			16.5		
	200			16.6		
	400			16.9		
	600			17.6		
	800			18.2		
	1 000			18.7		
C 0.20 Si 1.00 Mn 0.80 Ni 12.0 Cr 23.0 W 3.0 25% Cr 12% Ni 3% W BS 1648 E Normalised	RT	7.90	502	—	12.6	87
	100			15.0		
	300			16.0		
	500			16.0		
	700			17.0		
	900			19.0		
	1 000			—	29.3	
C 0.20 Si 1.50 Mn 1.00 Ni 20.0 Cr 25.0 25% Cr 20% Ni BS 1648 F Normalised	RT	7.90	544	—	15.9	90
	100			16.5		
	200			16.9		
	400			17.5		
	600			18.3		
	800			19.2		
	1 000			20.0		

Notes:

1. Where *specific heats* are quoted at temperatures above RT the values have been determined over a range of 50 °C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

Table 14.11 PHYSICAL PROPERTIES OF STEELS—*continued*

Material and condition *Composition* %	*Temperature* °C	*Specific gravity* g cm^{-3}	*Thermal properties (see Notes)*			*Electrical resistivity* μΩ cm
			Specific heat J kg^{-1} K^{-1}	*Coefficient of thermal expansion* 10^{-6} K^{-1}	*Thermal conductivity* W m^{-1} K^{-1}	
C 0.35 Si 0.90 Mn 0.75 Ni 25.0 Cr 15.0 25% Ni 15% Cr BS 1648 G	RT	7.90	502	—	12.6	88
	100			15.0		
	300			16.0		
	500			17.0		
	700			17.0		
	900			18.0		
	1 000				29.3	
C 0.50 Si 2.00 Mn 1.50 Ni 35.0 Cr 15.0 35% Ni 15% Cr Cast	RT	7.93	460	—	—	100
	100			—	13.4	
	500			16.0		
	800			16.5		
	1 100			17.6		
C 0.50 Si 2.0 Mn 1.50 Ni 40.0 Cr 20.0 40% Ni 20% Cr BS 1648 H Cast	RT	8.02	460	—	—	105
	100			—	13.4	
	500			16.0	—	
	800			16.4	23.9	
	1 100			17.4	—	
C 0.50 Si 2.00 Mn 1.50 Ni 60.0 Cr 15.0 60% Ni 15% Cr BS 1648 K Cast	RT	8.12	460	—	—	108
	100			—	13.4	
	500			14.2	—	
	800			15.3	23.0	
	1 100			16.5	—	

Notes:

1. Where *specific heats* are quoted at temperatures above RT, the values have been determined over a range of 50°C up to the temperature quoted.
2. *Coefficients of expansion* are mean values from RT, up to the temperature quoted.
3. *Electrical resistivity* values are uncorrected for dimensional changes of the specimen with temperature. Original dimensions as at RT.

REFERENCES TO TABLE 14.11

1. 'Metals Handbook', 4th edn.
2. J. Woolman and R. A. Mottram, 'Mechanical and Physical Properties of BS En Steels (BS 970, 1950), Pergamon Press.
3. Sundry technical information issued by industrial organizations e.g. British Steel Corporation, Mond Nickel Co. Ltd.

Table 14.12 SOME LOW TEMPERATURE THERMAL PROPERTIES OF A SELECTION OF STEELS

There is particular interest in the thermal properties (especially the thermal expansion) of steels used under conditions well below normal atmospheric temperature, and available information is set out below in respect of some such steels.

Material and condition *Analyses %*	*Temperature* °C	*Coefficient of thermal expansion* $10^{-6}K^{-1}$	*Thermal conductivity* $Wm^{-1}K^{-1}$
Typically	−200	−9.5	16.0
C 0.09 } 9 Ni	−150	−9.7	19.5
Ni 9 }	−100	−9.9	23.0
Double normalized and tempered	−50	−10.2	26.5
	RT	10.5	29.5
	100	11.0	32.0
	200	11.7	34.0
	300	12.3	34.5
C 0.42 } 1½ Ni–Cr–Mo	−150	−10.4	
Ni 1.58 }	−100	−11.2	
Cr 1.19 }	−50	−11.8	
Mo 0.24 }	RT	12.1	
Hardened 840°C OQ			
Tempered 650°C (1 h)/AC			
C 0.12 } ½ Mo–B	−150	−10.5	
Mo 0.54 }	−100	−11.2	
B 0.003 }	−50	−11.8	
Hardened 960°C OQ	RT	12.2	
Tempered 700°C (½ h) AC			
C 0.27 } 3 Cr–Mo	−150	−9.8	
Cr 3.14 }	−100	−10.3	
Mo 0.49 }	−50	−10.8	
Hardened 900°C OQ	RT	11.5	
Tempered 650°C (1 h) AC			
C 0.09 } 15 Cr–10 Ni–6 Mn–Mo–V–B–Nb			
Mn 6.23 }			
Ni 9.88 }	−150	−14.7	
Cr 14.88 }	−100	−15.3	
Mo 1.01 }	−50	−15.7	
V 0.28 }	RT	16.2	
B 0.003 }			
Nb 0.94 }			
1150°C AC			
C 0.13 } 4½ Ni–Cr–Mo	−150	−9.4	
Ni 4.16 }	−100	−9.8	
Cr 1.23 }	−50	−10.2	
Mo 0.19 }	RT	10.8	
Blank carburized 890°C AC			
820°C (¼ h), transferred to 580°C (½ h) OQ			
C 0.41 } 3 Cr–1 Mo–V	−150	−9.7	
Cr 3.14 }	−100	−10.1	
Mo 0.97 }	−50	−10.5	
V 0.20 }	RT	11.2	
Hardened 930 C OQ			
Tempered 700 (½ h) AC			
C 0.12 } 3½ Ni–Cr–Mo	−150	−10.1	
Ni 3.10 }	−100	−10.6	
Cr 0.91 }	−50	−11.0	
Mo 0.16 }	RT	11.6	
Blank carburized 910 C AC			
Hardened 840 C (½ h) OQ			
Tempered 760 C OQ			

Table 14.12 SOME LOW TEMPERATURE THERMAL PROPERTIES OF A SELECTION OF STEELS—*continued*

Material and condition *Analyses %*	*Temperature* °C	*Coefficient of thermal expansion* $10^{-6}K^{-1}$	*Thermal conductivity* $W\,m^{-1}\,K^{-1}$
C 0.99, Cr 1.47 } 1 C–1½ Cr	−150	−9.6	
	−100	−10.6	
Hardened 850°C AC	−50	−11.6	
Tempered 650°C (½h) AC	RT	12.3	
C 0.17, Ni 1.74, Cr 0.2, Mo 0.22 } 2 Ni–Mo En 34	−150	−8.5	
	−100	−9.5	
	−50	−10.4	
	RT	11.3	
Blank carburized 910°C AC			
Hardened 870°C OQ			
Tempered 770°C OQ			
C 0.11, Ni 3.04 } 3 Ni	−150	−9.9	
	−100	−10.5	
Blank carburized 910°C AC	−50	−11.0	
Hardened 870°C OQ	RT	11.5	
Tempered 770°C OQ			

• Thermal expansion values shown for temperatures other than RT are the mean values from RT to that temperature. For RT the instantaneous value is given.

REFERENCE TO TABLE 14.12

1. Sundry technical information issued by British Steel Corporation and Mond Nickel Co. Ltd.

15 Elastic properties, damping capacity and shape memory alloys

15.1 Elastic properties

The elastic properties of a metal reflect the response of the interatomic forces between the atoms concerned to an applied stress. Since the bonding forces vary with crystallographic orientation the elastic properties of metal single crystals may be highly anisotropic. However, polycrystalline metals and alloys with a randomly oriented grain structure behave isotropically. Table 15.1 lists elastic constants for polycrystalline metals and alloys in an isotropic condition. Any preferred orientation or texture resulting from rolling, drawing or extrusion, for example, will result in departures from the listed values to a degree that depends upon the elastic anisotropy of the individual crystals (which may be deduced from the single crystal elastic constants of Tables 15.2 to 15.6 that follow) and the nature and extent of the preferred orientation.

Since the elastic properties are determined by the aggregate response of the interatomic forces between all the atoms in the metal, the presence of small quantities of solute atoms in dilute alloys or their rearrangement by heat treatment will have relatively little effect on the absolute values of their elastic constants. Consequently, the elastic constants of all the plain carbon and low alloy steels will be approximately the same unless some preferred orientation is present. Similarly with Cu-, Al- and Ni- base dilute alloys, etc. In the case of concentrated alloys there may be larger variations in elastic moduli, especially where there is a drastic change in the relative proportions of different phases in a multiphase alloy. In the case of ideal solid solutions the elastic moduli vary linearly with atom fraction. The elastic moduli of non-ideal solid solutions may show positive or negative deviations from linearity. Ordering produces an increase in elastic moduli.

Increase in temperature causes a gradual decrease in elastic moduli. The decrease is fairly linear over wider ranges of temperature but sharply increases in magnitude as the melting point is approached. Discontinuities are observed at structural transformations.

Ferromagnetic materials having a high degree of domain mobility may exhibit considerably higher elastic moduli below the Curie point in the presence of a high magnetic field. The lower elastic moduli in the absence of a magnetic field are due to magnetostrictive dimensional changes caused by stress-induced domain movement.

Table 15.1 ELASTIC CONSTANTS OF POLYCRYSTALLINE METALS AT ROOM TEMPERATURE

Metal	*Young's modulus* GPa	*Rigidity modulus* GPa	*Bulk modulus* GPa	*Poisson's ratio*	*Ref.*
Aluminium	70.6	26.2	75.2	0.345	1
Antimony	54.7	20.7	—	0.25–0.33	2, 3
	77.9	19.3	—	—	4
Barium	12.8	4.86	—	0.28	2
Beryllium	318	156	110	0.02	5
Bismuth	34.0	12.8	—	0.33	2
Brass 70Cu 30Zn	100.6	37.3	111.8	0.35	1
Cadmium	62.6	24.0	51.0	0.30	5
Caesium	1.7	0.65	—	0.295	2
Calcium	19.6	7.9	17.2	0.31	2, 6
Cast Iron—Grey, BS 1452:1977					
Grade 150	100	40	—	0.26	7, 8
Grade 180	109	44	—	0.26	7, 8
Grade 220	120	48	—	0.26	7, 8
Grade 260	128	51	—	0.26	7, 8
Grade 300	135	54	—	0.26	7, 8
Grade 350	140	56	—	0.26	7, 8
Grade 400	145	58	—	0.26	7, 8
—Blackheart malleable BS 310:1972					
Grades B340/12 to B290/6	169	67.6	—	0.26	7, 9
Pearlitic malleable BS 3333:1972					
Grades P4440/7 to P540/5	172	68.8	—	0.26	7, 9
Whiteheart malleable BS 309:1972					
Grades W340/3, W410/4	176	70.4	—	0.26	7, 9
Nodular BS 2789:1973					
Grades 370/17, 420/12	169	66	—	0.275	7, 10
Grades 500/7, 600/3	169–174	65.9	—	0.275	7, 10
Grades 700/2, 800/2 (pearlitic, normalized)	176	68.6	—	0.275	7, 10
pearlite 700/2, 800/2 (hardened, tempered)	172	67.1	—	0.275	7, 10
Cerium	33.5	13.5	—	0.248	11, 12
Chromium	279	115.3	160.2	0.21	1
Cobalt	211	82	181.5	0.32	13, 16
Constantan 45Ni 55Cu	162.4	61.2	156.4	0.327	1
Copper	129.8	48.3	137.8	0.343	1
Cupro-nickel 70Cu 30Ni	144	53.8	—	0.34	14
Duralumin	70.8	26.3	75.4	0.345	1
Gallium	9.81	6.67	—	0.47	2
Germanium	79.9	29.6	—	0.32	2
Gold	78.5	26.0	171	0.42	15, 16
Hafnium	141	56	109	0.26	17, 18
Incoloy 800 20Cr, 32Ni bal Fe	196	73	—	0.334	38
Indium	10.6	3.68	—	0.45	2
Invar 64Fe 36Ni	144	57.2	99.4	0.259	1
Iridium	528	209	371	0.26	16, 19, 20, 21
Iron (pure)	211.4	81.6	169.8	0.293	1
Lanthanum	37.9	14.9	—	0.28	2, 12
Lead	16.1	5.59	45.8	0.44	1
Lithium	4.91	4.24	—	0.36	23, 28
Magnesium	44.7	17.3	35.6	0.291	1
Manganese	191	79.5	—	0.24	2, 24

Table 15.1 ELASTIC CONSTANTS OF POLYCRYSTALLINE METALS AT ROOM TEMPERATURE—*continued*

Metal	*Young's modulus* GPa	*Rigidity modulus* GPa	*Bulk modulus* GPa	*Poisson's ratio*	*Ref.*
Manganese–copper 70Mn 30Cu (high damping alloy)	93	22.4	—	—	25
Molybdenum	324.8	125.6	261.2	0.293	1
Monel 400 63–70Ni, 2 Mn, 2.5Fe, bal Cu	185	66	—	0.32	26
Nickel	199.5	76.0	177.3	0.312	1
Nickel silver 55Cu, 18Ni, 27 Zn	132.5	49.7	132	0.333	1
Nimonic 80A 20Cr, 2.3Ti, 1.8Al, bal Ni (fully heat-treated)	222	85	—	0.31	27
Niobium	104.9	37.5	170.3	0.397	1
Ni–span C902 (constant modulus alloy)	186	66	—	0.41	28
Osmium	559	223	373	0.25	16, 21, 29
Palladium	121	43.6	187	0.39	18, 19, 21, 29
Platinum	170	60.9	276	0.39	16, 19, 29, 30
Plutonium	87.5	34.5	—	0.18	31
Potassium (−190°C)	3.53	1.30 (room temp.)	—	0.35	15
Rhenium	466	181	334	0.26	2, 16 32
Rhodium	379	147	276	0.26	16, 19,29
Rubidium	2.35	0.91	—	0.30	2
Ruthenium	432	173	286	0.25	18, 21,29
Selenium	58	—	—	0.447	15
Silicon	113	39.7	—	0.42	2, 33
Silver	82.7	30.3	103.6	0.367	1
Sodium	6.80	2.53	—	0.34	2, 23
Steel—Mild	208–209	81–82	160–169	0.27–0.3	34
0.75C	210	81.1	168.7	0.293	1
0.75C (hardened)	201.4	77.8	165	0.296	1
Tool 0.98C, 1.03 Mn, 0.65 Cr, 1.01 W	211.6	82.2	165.3	0.287	1
Tool 0.98C, 1.03 Mn, 0.65 Cr, 1.01 W (hardened)	203.2	78.5	165.2	0.295	1
Maraging Fe–18Ni 8Co 5Mo	186	72	—	0.30	35
Stainless austenitic (Fe–18Cr, 8–10 Ni)	190–201	74–86	—	0.25–0.29	36
	200–206	78–79	—	0.27–0.3	36
Stainless, ferritic (Fe–13Cr)	200–215	80–83	—	0.27–0.3	1, 36
Stainless, martensitic (Fe–13Cr, 0.1–0.3C)	215.3	83.9	166	0.283	1
Stainless, martensitic (Fe–18Cr, 2Ni, 0.2C)					
Strontium	15.7	6.03	12.0	0.28	2, 6
Tantalum	185.7	69.2	196.3	0.342	1
Tellurium	47.1	16.7	—	0.16–0.3	15
Thallium	7.90	2.71	28.5	0.45	2, 6
Thorium	78.3	30.8	54.0	0.26	2, 6
Tin	49.9	18.4	58.2	0.357	1
Titanium	120.2	45.6	108.4	0.361	1
Tungsten	411	160.6	311	0.28	1
Tungsten carbide	534.4	219	319	0.22	1
Uranium	175.8	73.1	97.9	0.20	37
Vanadium	127.6	46.7	158	0.365	1
Yttrium	66.3	25.5	—	0.265	12
Zinc	104.5	41.9	69.4	0.249	1
Zirconium	98	35	89.8	0.38	17, 18

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15.1.1 Elastic compliances and elastic stiffnesses of single crystals

Single crystals are generally anisotropic and therefore require many more constants of proportionality than isotropic materials. The relations between stress and strain are defined by the generalized Hooke's law, which states that the strain components are linear functions of the stress components and vice versa.

That is,

$$\varepsilon_{xx} = S_{11}\sigma_{xx} + S_{12}\sigma_{yy} + S_{13}\sigma_{zz} + S_{14}\sigma_{yz} + S_{15}\sigma_{zx} + S_{16}\sigma_{xy}$$
$$\varepsilon_{yy} = S_{21}\sigma_{xx} + S_{22}\sigma_{yy} + S_{23}\sigma_{zz} + S_{24}\sigma_{yz} + S_{25}\sigma_{zx} + S_{26}\sigma_{xy}$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$\varepsilon_{xy} = S_{61}\sigma_{xx} + S_{62}\sigma_{yy} + S_{63}\sigma_{zz} + S_{64}\sigma_{yz} + S_{65}\sigma_{zx} + S_{66}\sigma_{xy}$$

and correspondingly

$$\sigma_{xx} = C_{11}\varepsilon_{xx} + C_{12}\varepsilon_{yy} + C_{13}\varepsilon_{zz} + C_{14}\varepsilon_{yz} + C_{15}\varepsilon_{zx} + C_{16}\varepsilon_{xy}$$
$$\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots$$
$$\sigma_{xy} = C_{61}\varepsilon_{xx} + C_{62}\varepsilon_{yy} + C_{63}\varepsilon_{zz} + C_{64}\varepsilon_{yz} + C_{65}\varepsilon_{zx} + C_{66}\varepsilon_{xy}$$

where

σ_{xx}, σ_{yy}, σ_{zz} and σ_{yz}, σ_{zx}, σ_{xy} represent normal and shear stresses, respectively;
ε_{xx}, ε_{yy}, ε_{zz} and ε_{yz}, ε_{zx}, ε_{xy} represent normal and shear strains, respectively.

The elastic constants S_{ij} and C_{ij} are called the elastic compliances and elastic stiffnesses, respectively. Many of the constants are equal, the number of independent constants decreasing with increasing crystal symmetry. For example, in the hexagonal system there are five independent constants, while in the cubic system there are only three elastic compliances S_{11}, S_{12}, S_{44} with corresponding elastic stiffnesses C_{11}, C_{12}, C_{44}.

The tensile and shear moduli will vary with orientation in a single crystal of a cubic metal according to

$$\frac{1}{E}=S_{11}-2[(S_{11}-S_{12})-\tfrac{1}{2}S_{44}]\,(l^2m^2+m^2n^2+l^2n^2)$$

$$\frac{1}{G}=S_{44}-2[(S_{11}-S_{12})-\tfrac{1}{2}S_{44}]\,(l^2m^2+m^2n^2+l^2n^2)$$

where l, m, n are the direction cosines of the specimen axis with respect to the crystallographic axes. For an isotropic crystal

$$S_{44}=2(S_{11}-S_{12}) \text{ and } C_{44}=\tfrac{1}{2}(C_{11}-C_{12})$$

hence

$$E=\frac{1}{S_{11}} \text{ and } G=\frac{1}{S_{44}}$$

Therefore, the degree of anisotropy is conveniently specified by

$$\frac{2(S_{11}-S_{12})}{S_{44}} \text{ or } \frac{(C_{11}-C_{12})}{2C_{44}}$$

15.1.2 Principal elastic compliances and elastic stiffnesses at room temperature

The units are TPa^{-1} for S_{ij} (elastic compliances) and GPa for C_{ij} (elastic stiffnesses).

Table 15.2 CUBIC SYSTEMS (3 CONSTANTS)

Metal	S_{11}	S_{44}	S_{12}	C_{11}	C_{44}	C_{12}	*Ref.*
Ag	22.9	22.1	−9.8	123	45.3	92.0	1
Al	16.0	35.3	−5.8	108	28.3	62.0	1, 2
Au	23.4	23.8	−10.7	190	42.3	161	1
Ca	94.0	83.0	−31.0	16.0	12.0	8.0	3
Cr	3.08	9.98	−0.49	346	100	66.0	1
Cs (78 K)	1676	676	−762	2.49	2.06	1.48	4
Cu	15.0	13.3	−6.3	169	75.3	122	1
Fe	7.67	8.57	−2.83	230	117	135	1
Ge	9.73	14.9	−2.64	129	67.1	48.0	1
Ir	2.24	3.72	−0.67	600	270	260	5
	2.28	3.90	−0.67	580	256	242	6
K	1215	531	−558	3.71	1.88	3.15	7
	1339	526	−620	3.69	1.90	3.18	8
Li	315	104	−144	13.4	9.60	11.3	9
Mo	2.71	9.0	−0.74	459	111	168	1
Na	549	233	−250	7.59	4.30	6.33	1
Nb	6.56	35.2	−2.29	245	28.4	132	1, 10, 11

Table 15.2 CUBIC SYSTEMS (3 CONSTANTS)—*continued*

Metal	S_{11}	S_{44}	S_{12}	C_{11}	C_{44}	C_{12}	*Ref.*
Ni (zerofield)	7.67	8.23	−2.93	247	122	153	1, 12
Ni (saturation field)	7.45	8.08	−2.82	249	124	152	1
Pb	93.7	68.0	−43.0	48.8	14.8	41.4	1
Pd	13.7	14.0	−6.0	224	71.6	173	1
Pt	7.35	13.1	−3.08	347	76.5	251	13
Rb	1 330	625	−600	2.96	1.60	2.44	14
Si	7.74	12.6	−2.16	165	79.2	64	1
Sr	148	174	−60	14.7	5.74	9.9	15
Ta	6.89	12.1	−2.57	262	82.6	156	1, 16
Th	27.2	20.9	−10.7	75.3	47.8	48.9	17
	27.4	22.0	−10.9	77.0	45.5	50.9	18
Tl	101	91	−46	40.8	11.0	34.0	19
V	6.76	23.2	−2.32	230	43.2	120	1
W	2.49	6.35	−0.70	517	157	203	1

Table 15.3 HEXAGONAL SYSTEMS (5 CONSTANTS)

Metal		11	33	44	12	13	*Ref.*
Be	S	3.45	2.87	6.16	−0.28	−0.05	1
	C	292	349	163	24	6	1
Cd	S	12.2	33.8	51.1	−1.2	−8.9	1
	C	116	50.9	19.6	42	41	1
Co	S	5.11	3.69	14.1	−2.37	−0.94	1
	C	295	335	71.0	159	111	1
Dy	S	16.0	14.5	41.2	−4.6	−3.2	1
	C	74.0	78.6	24.3	25.5	21.8	1
Er	S	14.1	13.2	36.4	−4.2	−2.6	1
	C	84.1	84.7	27.4	29.4	22.6	1
Gd	S	18.3	16.1	48.3	−5.7	−3.8	20
	S	18.0	16.1	48.1	−5.7	−3.6	21
	C	66.7	71.9	20.7	25.0	21.3	20
	C	67.8	71.2	20.8	25.6	20.7	21
Hf	S	7.16	6.13	18.0	−2.48	−1.57	22
	C	181	197	55.7	77	66	22
Ho	S	15.3	14.0	38.6	−4.3	−2.9	1
	C	76.5	79.6	25.9	25.6	21.0	1
Mg	S	22.0	19.7	60.9	−7.8	−5.0	1
	C	59.3	61.5	16.4	25.7	21.4	1
Nd	S	23.7	18.5	66.5	−9.50	−3.90	23, 24
	C	54.8	60.9	15.0	24.6	16.6	23, 24
Pr	S	26.6	19.3	73.6	−11.3	−3.80	25, 26
	C	49.4	57.4	13.6	23.0	14.3	25, 26
Re	S	2.11	1.70	6.21	−0.80	−0.40	1
	C	616	683	161	273	206	1
Ru	S	2.09	1.82	5.53	−0.58	−0.41	20
	C	563	624	181	188	168	20
Sc	S	12.5	10.6	36.1	−4.30	−2.20	27
	C	99.3	107	27.7	39.7	29.4	27
Tb	S	17.4	15.6	46.0	−5.2	−3.60	21, 28
	C	69.2	74.4	21.8	25.0	21.8	21, 28
Tl	S	104	31.1	139	−83.0	−11.6	29, 30
	C	41.9	54.9	7.20	36.6	29.9	29, 30
Ti	S	9.69	6.86	21.5	−4.71	−1.82	1
	C	160	181	46.5	90.0	66.0	1
Y	S	15.4	14.4	41.1	−5.10	−2.70	31
	C	77.9	76.9	24.3	29.2	20.0	31
Zn	S	8.22	27.7	25.3	−0.60	−7.0	1, 32
	C	165	61.8	39.6	31.1	50.0	1
Zr	S	10.1	8.0	30.1	−4.0	−2.4	1
	C	144	166	33.4	74	67	1

Table 15.4 TRIGONAL SYSTEMS (6 CONSTANTS)

Metal		11	33	44	12	13	14	*Ref.*
As	S	30.6	140	45.0	20.5	−56.0	1.7	33
	C	130	58.7	22.5	30.3	64.3	−3.7	33
Bi	S	25.7	41.1	113	−7.8	−11.2	−21.4	1, 34
	C	62.3	37.0	11.5	23.1	23.4	7.3	1, 34
B	S	—	—	—	—	—	—	—
	C	467	473	198	241	—	15.1	35
Hg (83 K)	S	154	45.0	151	−119	−21	−100	36
	C	36.0	50.5	12.9	28.9	30.3	4.7	36
Sb	S	16.0	29.6	39.1	−6.1	−6.0	−12.4	1
	C	101	44.8	39.6	31.4	27.0	22.1	1
Se	S	131	41	112	−13	−40	56	1
	C	18.6	76.1	14.8	7.3	25.2	5.6	1
Te	S	53.4	24.3	52.1	−16.1	−13.6	26.7	1
	C	34.4	70.8	32.7	9.0	24.9	13.1	1

Table 15.5 TETRAGONAL SYSTEMS (6 CONSTANTS)

Metal		11	33	44	66	12	13	*Ref.*
In	S	149	199	154	83	−44	−96	1
	C	45.2	44.9	6.52	12.0	40	41.2	1
Sn	S	42.4	14.8	45.6	42.1	−32.4	−4.3	1
	C	73.2	90.6	21.9	23.8	59.8	39.1	1

Table 15.6 ORTHORHOMBIC SYSTEMS (9 CONSTANTS)

Metal		11	12	33	44	55	66	12	13	23	*Ref.*
Ga	S	12.2	14.0	8.49	28.6	23.9	24.8	−4.4	−1.7	−2.4	1
	C	100	90.2	135	35.0	41.8	40.3	37.0	33.0	31.0	1
U	S	4.91	6.73	4.79	8.04	13.6	13.4	−1.19	0.08	−2.61	37
	C	215	199	267	124	73.4	74.3	46.5	21.8	108	37

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15.2 Damping capacity

The damping capacity of a metal measures its ability to dissipate elastic strain energy. The existence of this property implies that Hooke's law is not obeyed even at stresses well below the conventional elastic limit. In a perfectly elastic solid in vibration, stress and strain are always in phase and no energy is dissipated.

There are two important types of damping: anelastic and hysteretic.

In an anelastic solid there is a lag between the application of stress and the attainment of the resulting equilibrium strain; unless the stress changes exceedingly slowly. Processes with this characteristic give rise to an energy loss that reaches a peak at a critical frequency of vibration.

An hysteretic solid has a stress–strain curve on loading that does not coincide with that on unloading. The area between the two curves is proportional to the energy loss and does not vary with the frequency with which the load cycle is traversed but changes in a complex fashion with peak stress. Damping from this class of mechanism is often high and since it does not vary with frequency is of particular interest to the engineer since it can contribute to vibration and noise reduction and can limit the intensity of vibrational stress under resonant conditions and thus minimize fatigue failure.

Table 15.7 lists the specific damping capacity of a number of commercial alloys including some of very high damping that might be of interest to vibration engineers. In all cases the damping is predominantly of the hysteretic type.

Table 15.7 THE SPECIFIC DAMPING CAPACITY OF COMMERCIAL ALLOYS AT ROOM TEMPERATURE

The specific damping capacity which is normally measured on solid cylinders stressed in torsion is defined as the ratio of the vibrational strain energy dissipated during one cycle of vibration to the vibrational strain energy at the beginning of the cycle.

Alloy	*Composition %*	*Specific damping capacity %*	*Surface shear stress* MPa
Cast irons			
High carbon inoculated flake iron	2.5% C, 1.9% Si, 1.0% Mn, 20.7% Ni, 1.9% Cr, 0.13% P	19.3	34.5
Spun cast iron	3.54% C, 3.39% G.C., 1.9% Si, 0.4% Mn, 0.38% P	10.8	34.5
Non-inoculated flake iron	3.3% C, 2.2% Si, 0.5% Mn, 0.14% P, 0.03% S	8.5	34.5
Inoculated flake iron	3.3% C, 2.2% Si, 0.5% Mn, 0.14% P, 0.03% S	7.3	34.5
Austenitic flake graphite	2.5% C, 1.9% Si, 1% Mn, 20.7% Ni, 1.9% Cr, 0.03% P, 0.03% S	7.1	34.5
Alloyed flake graphite	3.14% C, 2% Si, 0.6% Mn, 0.7% Ni, 0.4% Mo, 0.14% P, 0.03% S	5.3	34.5
Nickel-copper austenitic flake	2.55% C, 1.9% Si, 1.25% Mn, 15.2% Ni, 7.3% Cu, 2% Cr, 0.03% P, 0.04% S	3.9	34.5
Undercooled flake graphite titanium/CO_2 treated	3.27% C, 2.2% Si, 0.6% Mn, 0.35% Ti, 0.14% P, 0.03% S	3.9	34.5
Annealed ferritic nodular	3.7% C, 1.8% Si, 0.4% Mn, 0.76% Ni, 0.06% Mg, 0.03% P, 0.01% S, <0.003% Ce	2.8	34.5

Table 15.7 THE SPECIFIC DAMPING CAPACITY OF COMMERCIAL ALLOYS AT ROOM TEMPERATURE—*continued*

Alloy	*Composition %*	*Specific damping capacity %*	*Surface shear stress* MPa
Pearlitic malleable	BS 3333/1961 Grade B.33/4	1.6	34.5
Blackheart malleable	BS 310/1958 Grade B.22/14	1.5	34.5
As cast pearlitic nodular	3.66% C, 1.8% Si, 0.4% Mn, 0.76% Ni, 0.06% Mg, 0.03% P, 0.01% S, < 0.003% Ce	1.4	34.5
Steels			
BS 970 070M20 En3	0.17% C mild steel, normalized	1.5	34.5
BS 1407 (silver steel)	Spherodized	0.8	34.5
BS 1407 (silver steel)	Water quenched 800 °C	0.5	34.5
BS 1407 (silver steel)	Water quenched 800 °C aged 100 °C 1½ h	0.2	34.5
BS 970 653M31 En23T	3% Ni, 1% Cr, 0.3% C	0.8	34.5
BS 970 503M40 En12Q	1% Ni, 0.4% C	0.3	34.5
BS 970 709M40 En19U	1% Cr, 0.3% Mo, 0.4% C	0.15	34.5
BS 3S62	12% Cr, 0.2% C. Quenched tempered to 225 BHN	3.8	34.5
BS 970 321S20 En58B	18% Cr, 8% Ni, 0.6% Ti, 0.1% C. Solution treated 1 050 °C water quenched	1.8	34.5
NMC	0.62% C, 3.86% Cr, 8.6% Ni, 7.3% Mn. Solution treated 1 050 °C, water quenched	0.7	34.5
BS 970 302S25 En58A	18% Cr, 8% Ni, 0.1% C. Solution treated 1 050 °C, water quenched	0.3	34.5
Copper alloys			
Hidurel 6	As cast	1.35	34.5
Gunmetal	88% Cu, 10% Zn, 2% Sn	1.0	34.5
Brass (BS 265)	As extruded	0.4	34.5
Hidurel 5	As cast	0.4	34.5
Hidurel 7	As cast	0.25	34.5
High tensile brass	As cast	0.25	34.5
Novoston	—	0.25	34.5
Incramute	58% Cu, 40% Mn, 2% Al, aged 400 °C	68	
Aluminium alloys			
Duralumin (HE 14)	— —	0.25	34.5
RR57 (DTD 5004 WP)	—	0.20	34.5
RR58 (DTD 5014 WP)	—	0.10	34.5
Hiduminium 100 (SAP)	—	5.0	34.5
Magnesium alloys			
DTD 5005	Mg/Zn/Zr/Th	7.4	20.7
BS 1278	Mg/Zn/Mn	1.6	20.7
DTD 721A	Mg/Zn/Zr	0.65	20.7
Magnesium Elektron MSR Alloy	Mg/Ag/Zr	0.4	20.7
Manganese alloys			
Mn–Cu (quenched from 850 °C aged 2 h at 425 °C)	90% Mn–10% Cu	21	34.5
	85% Mn–15% Cu	27	34.5
	80% Mn–20% Cu	22	34.5
	70% Mn–30% Cu	42	34.5
	60% Mn–40% Cu	42	34.5
	50% Mn–50% Cu	33	34.5
Mn–Cu (sintered)	40wt% Cu–60wt% Mn	> 40	35
Nickel alloys			
Ni–Ti (Nitinol)	55% Ni–45% Ti	26	69
T–D Nickel	2.5% Thoria	10.7	69
Mallory No-chat	—	9.4	69
Titanium alloys			
Ti–Al–V–Mo	Ti–5.5–6.75% Al–1–5% V–1–5% Mo (V + Mo > 6%), all wt%	0.5	

Reference: D. Birchon, *Engineering Materials and Design*, Sept., Oct., 1964; also 307, 312.

15.2.1 Anelastic damping

Of interest to the physical metallurgist is the fact that a phase lag between stress and strain can give rise to a peak in energy dissipation or damping as a function of temperature or frequency. Several quite distinct atomic processes have been identified with damping peaks and measurements on these peaks in a wide variety of metals and alloys have been used to give diffusion data and to study precipitation, ordering phenomena and the properties of dislocations, point defects and grain boundaries. Table 15.8 identifies the damping peaks found in a number of pure metals and alloys with the relaxation process thought to be involved and also give an indication of the magnitude of the damping peak height. Detailed information on the specific mechanisms involved can be obtained from the reviews below and the references given for the respective damping peaks. The main types of peak that are observed are as follows. In cold worked pure metals movement of dislocation lines results in a number of low temperature peaks known as Bordoni peaks. Interaction of dislocations with point defects give rise to a further series of unstable peaks at higher temperatures; these are now called Hasiguti peaks. In alloys the stress-induced redistribution of solute atoms results in two types of peak, the Zener-type peak in substitutional solid solutions and the Snoek-type peak in interstitial solid solutions. The interaction of interstitial solute atoms with substitutional solute atoms give rise to a modified Snoek peak in ternary alloys. In cold worked alloys the interaction of interstitial solute atoms with dislocations results in the Köstler-type peaks at higher temperatures than the Snoek-type peaks. In pure metals and alloys the stress-induced migration of grain boundaries and/or polygonised (sub-grain) boundaries give rise to a further series of high temperature damping peaks.

In the ideal case, for a relaxation process having a single relaxation time (τ) the logarithmic decrement (δ) will be given by

$$\delta = \pi\Delta\frac{\omega\tau}{1+\omega^2\tau^2}$$

where ω is the angular frequency and Δ is the modulus defect. The relaxation time, being diffusion controlled, varies with temperature according to an Arrhenius equation of the form $\tau = \tau_0 \exp(H/RT)$ where τ_0 is a constant, H is the activation energy controlling the relaxation process and T is the absolute temperature. The condition for maximum damping (δ_p) is that $\omega\tau = 1$ and hence

$$\delta_p = \frac{\pi\Delta}{2} (= \pi Q^{-1} \text{ max})$$

The modulus defect which is a measure of the strength of the relaxation can be highly orientation dependent and therefore the values given in the table below must be interpreted with caution. It must also be noted that for many measured damping peaks a distribution of relaxation times is found to be present. This leads to a broader peak being observed than would be present if a single relaxation time were operative. The decrement will be given by

$$\delta = \pi\sum_i \Delta_i \frac{\omega\tau_i}{1+\omega^2\tau_i^2}$$

where each i refers to a component of the total peak that has the same form as that of a peak arising from a single relaxation time.

This theoretical aspect of the analysis of broad peaks in terms of a spectrum of τ's has been comprehensively dealt with by A. S. Nowick and B. S. Berry in *IBM Journal of Research and Development*, 1961, 5(4), 297–311, 312–20.

REVIEWS

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In Table 15.8, metals and alloys are listed in alphabetical order with the highest concentration constituent first. The values of the modulus defect are deduced using the equation

$$\Delta = \frac{2\delta_p}{\pi} = 2Q^{-1}_{\max}$$

where δ_p is the peak decrement and $Q^{-1}_{\max}$ is the peak value of Q^{-1}. These relationships are valid only if the damping arises from a process having a single relaxation time. In most cases a distribution of relaxation times exists and the peaks are broader, but there is only rarely sufficient published data to permit this distribution to be deducted. As many authors do not make it clear which damping units they use, the quoted values of Modulus Defect in the table must not be interpreted too precisely. The aim is to record the existence of peaks and list the suggested mechanism giving rise to them, and the values of Δ serve to indicate the approximate strength of the relaxation. If detailed quantitative data are sought peaks should be analysed in particular cases using the method of Berry and Nowick.

Table 15.8 ANELASTIC DAMPING

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Ag	99.999% Ag	37 K	0.7	2.6×10^{-2}	0.84	Bordoni type	1, 2
	(CW* 16% at 4.2 K)	50 K	0.7	1.2×10^{-2}	0.84	Bordoni type	1, 2
Ag	99.999% Ag single crystal deformed at RT 43.7% [121] 5.4% [111]	~50 K	~600	13×10^{-4}	—	Bordoni type	3
	Single crystals deformed at (5.4% [111]) RT	~50 K	~600	6×10^{-3}	—	Bordoni type	3
Ag	99.99% Ag	173 K	10^3	—	21.3	Point defect/ dislocation interaction	4
	(CW* at RT)	200 K	10^3	—	35.6 etc.	Point defect/dislocation interaction	4
Ag	99.998% Ag (84% area reduction, then annealed at 500°C for 1 h)	163°C	1.04	38×10^{-4}	92.0	Grain boundary	5
		356°C	0.98	39×10^{-4}	177	Grain boundary	5
Ag	99.999% Ag	150 K	1.5	1.3×10^{-2}	92	Grain boundary	6
Ag–Au	25–80 At. % Au	364–398°C	1.0	2×10^{-3}–2×10^{-2}	175.7–165.3	Zener	7
	42 At. % Au	460°C	0.36	0.104 max		Grain boundary	8
Ag–Cd	29 At. % Cd	~230°C	~1	—	152.3	Zener	9
	39 At. % Cd	—	~1	—	123.0	Zener	9
Ag–Cd	32 At. % Cd	220°C	0.6	4×10^{-2}	146.9	Zener	10
	0.9–32 At. % Cd	367–452°C	1.5	9.2×10^{-2}–1.38×10^{-1}	159–188	Grain boundary	6, 11
Ag–In	9.6 At. % In–17.9 At. % In	580–536 K	~1	$<3.5\times10^{-3}$–7×10^{-3}	152.8–130.5	Zener	12
Ag–In	7.5 At. % In–15.6 At. % In	—	~1	6.5×10^{-4}–6×10^{-3}	159–133.1	Zener	9
Ag–In	10.8 At. % In–18.1 At. % In	~500 K	10^{-3}–10^{-1}	$\sim20\times10^{-3}$	146.9–139.7	Zener	13
Ag–In	16 At. % In	270°C	1.6	2.9×10^{-2}	—	Zener	14
Ag–In	1 At. % In–16 At. % In	355–450°C	1.5	9.5×10^{-2}–1.27×10^{-1}	172–188	Grain boundary	6, 11
Ag–Sb	6.3 At. % Sb	~510 K	10^{-3}–10^{-1}	$\sim5\times10^{-3}$	136	Zener	15
Ag–Sn	0.93 At. % Sn	200°C	1.5	1.3×10^{-3}	—	Zener	6, 11
Ag–Sn	8.1 At. % Sn	~550 K	10^{-3}–10^{-1}	$\sim5\times10^{-3}$	131.8	Zener	15
Ag–Sn	0.9 At. % Sn–8.0 At. % Sn	390–440°C	1.5	1.08×10^{-1}–1.27×10^{-1}	171–184	Grain boundary	6, 11
Ag–Zn	15 At. % Zn–30 At. % Zn	280–232°C	0.68	1.2×10^{-2}–1.4×10^{-2}	142–136	Zener	16

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Al	99.99% Al (CW* 3% at RT)	24 K	1.2×10^{4}	1.5×10^{-4}	2.3	Bordoni type	17, 18
Al	99.999% Al deformed at 20 K then at 80 K	70 K	3	—	11.6	Bordoni type	19
		100 K	3	—	18.3	Bordoni type	
		115 K	3	—	—	?	
		155 K	3	—		?	
Al	99.99% Al (CW* 6% at RT)	83 K	1.08×10^{3}	1.6×10^{-3}	16.3	Bordoni type	20
		119 K	1.06×10^{3}	2.4×10^{-3}	28.9	Bordoni type	
Al	99.999% Al 2 h at 470 K, then CW* by 0.5% at 77 K	110 K	4×10^{-2}	$\sim10^{-2}$	24	Hasiguti type	21
		155 K	2×10^{3}	$\sim2\times10^{-3}$	—	Hasiguti type	
Al	99.999% Al deformed at 85 K by 10^{-4} and cycled 10^{2} times	130 K	~1	$\sim30\times10^{-3}$	—	Bordoni type with contribution from impurity–dislocation interactions	22
Al	99.994% [111]	139 K	10^{7}–	—	4.1	Bordoni type	23
	[100]	153 K	5×10^{7}	—	6.0	Bordoni type	
	[110]	196 K		—	19.5	Bordoni type	
Al	99.999% Al (CW* 18% at RT)	213 K	10^{3}	—	38.5	Point defect/dislocation interaction	4
Al	99.6% Al reduced by 69%	270°C	5×10^{-1}	$\sim1.2\times10^{-1}$	—	Relaxation of stresses by shear deformation and recrystallization	24
Al	99.6% Al reduced by 99.3%	270°C	5×10^{-1}	$\sim2\times10^{-1}$	—	Relaxation of stresses by shear deformation and recrystallization	24
		400°C	5×10^{-1}	$\sim10^{-1}$	—	Associated with grain boundaries	24
Al	99.999% Al deformed by 65%, annealed and deformed again	~300°C	~1	10^{-3}–10^{-2} depending on CW	48.2	Associated with dislocations	25
Al	99.96% Al area reduced by 75% annealed at 325°C for 2 h	340°C	2.32	7.85×10^{-2}	144.3	Grain boundary	5
Al	99.991% Al	275°C	0.69	1.4×10^{-1}	134	Grain boundary	26
Al	99.999% Al CW* 4% then irradiated by neutrons at 80 K, annealed 360 K	110 K	2.5	1.6×10^{-2}	—	Point defect/dislocation interaction	241
Al	99.9999wt% Al (bamboo boundaries)	~300°C	~1	1.44 eV		Grain boundary	251
Al	99.999wt% (3 h at 402°C)	396°C	8×10^{-3}	0.52	1.5 eV	Polygonization	256
Al	99.999wt% (single crystal sheet)	400°C	1.3			Dislocation network	258
Al	99.9999wt% Al (polycrystalline wires)						272
	(grain size ≪ wire dia.)	210°C	~1			Grain boundary	
	(grain size ≫ wire dia.)	170°C	~1			Not known	
Al	99.999wt% (single crystal)	365°C	1		184 eV	Point defects/dislocation interaction	265
Al–Ag	20% Ag (quenched from 520°C, aged at 155°C)	140°C	0.25	1.2×10^{-2}	105–113	Stress induced change of local degree of precipitation	27
Al–Ag	2.5% Ag–30% Ag annealed	~140–~170°C	~1	$\sim5\times10^{-4}$ $\sim8\times10^{-3}$	155	Diffusion controlled relaxation of partial dislocations around precipitates	28

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Al–Ag	15% Ag (quenched from 200°C)	160–210°C	0.45 0.45	$\sim 4 \times 10^{-3}$ $\sim 4 \times 10^{-3}$	— —	Associated with γ Associated with clustering	29
Al–Ag	Al + 30% Ag (1) quenched	410 K	—	8×10^{-3}	92	Zener in solid solution	247
	(2) aged at 520 K	420 K	—	14×10^{-3}	110	Zener in γ phase	247
Al–Ag	Al–2, 5, 10, 30wt% Ag (1 mm dia. wires of g.s. 0.75 mm)	400 K; 450 K; variable	~1			Zener; partial reversion of G.P. zones; gamma precipitation	301
Al–Cu	4% Cu (quenched from 520°C reverted at 200°C)	175°C	0.9	2×10^{-3}	128(117)	Zener	30, 31
Al–Cu	4% Cu (quenched, reverted, aged at 200°C for 144 h)	120°C	0.5	2.4×10^{-3}	92	Stress induced change of shape of precipitate	30
Al–Cu	Al–0.015wt% Cu (3 h at 402°C)	580°C	0.3	0.44		Polygonization	256
Al–Cu–Mg–Si	Quenched from 500°C, aged at 50°C	20°C	2×10^{3}	6×10^{-4} max	56.5	Stress induced ordering of complex atom group	32
Al–Fe	Al–0.25% Fe (annealed at 600°C for 6 h)	~280°C ~310°C	20– 2×10^{2}	$\sim 5 \times 10^{-4}$ $\sim 2 \times 10^{-3}$	117 167	? ?	33 33
Al–Fe	Al–0.06% Fe	~280°C	~1	Depends on grain size	~140	Grain boundary	34
Al–Fe	Al–0.16% Fe–0.5% Fe	310–360°C 440–480°C	~1 ~1	Depends on grain size	~140 200	Grain boundary Related to relaxation of stresses and precipitation of Fe on grain boundaries	34 34
Al–Fe–Ce	Rapidly quenched Al–8.6wt% Fe–3.8wt% Ce (extrusion compacted, rapidly solidified)	475 K	0.8	96×10^{-4}	150	Zener	263
Al–Mg–Si	Al–0.6% Mg–0.6% Si (quenched from 480°C and aged at 230°C for 26½ h)	215°C	2.25	5.5×10^{-2}	126	Stress induced diffusion of solutes (?)	35
Al–Mg	Al–0.03at% Mg (0.5% tensile strain at 208 K)	243 K; 333 K	~1		0.32 eV; 0.22 eV	Dragging of solute atoms and atom/vacancy pairs	299
Al–Mg	2% Mg	RT	2.5×10^{4}	1.2×10^{-5}	—	Thermoelastic	36
Al–Mg	5.45% Mg (quenched from 500°C, aged at 250°C)	165°C	1.5	7×10^{-4}	116.3	Zener	37
Al–Mg	7.5% Mg (annealed at 400°C then quenched)	~40°C	~2	—	66.9	Relaxation of solute clusters	38
		~80°C	~2	—	—	Zener	
		~120°C	~2	—	102.5	Zener	
		~227°C	~2	—	125.5	?	
Al–Mg	7.5% Mg (annealed at 400°C, cooled slowly)	~203°C	~2	—	125.5		
Al–Mg	0.93% Mg–12.1% Mg	~100–~200°C	0.4–98	10^{-4}–2×10^{-3}	135.0	Zener	39
Al–Mn–Fe–Si	Al–1.07wt% Mn–0.52wt% Fe–0.11wt% Si (cold worked and precipitated)	440 K	1			Ke, 3 times wider than single relaxation	305
Al–Si	Insoluble Si particles in Al	420 K	~1		0.92 eV	Relaxation at Al–Si interface	298
Al–Si	(solution-treated and aged)	110–180°C	1			Migrates and falls to zero during ageing; vacancy/Si clusters	311 312

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Al–Zn	3.7% Zn (quenched from 450°C to RT)	21°C	0.26	$\sim 2\times10^{-3}$	53	Stress induced ordering of zinc atom–vacancy complexes	40
Al050/SiC	Composite	300 K	0.07			Interface	252
Au	99.999% Au, (CW* 16% at 4.2 K)	43 K	0.5	1.4×10^{-1}	9.62	Bordoni type	1, 41
		65 K	0.5	1.6×10^{-1}	18.4	Bordoni type	1, 41
		77 K	0.5	1.6×10^{-1}	18.4	Bordoni type	1, 41
Au	99.999% Au (annealed at 1 170 K for 4 h, then CW* 3% at 77 K)	120 K	4×10^{-2}–2×10^{3}	$\sim10^{-4}$	—	Hasiguti type	21
		180 K		$\sim5\times10^{-3}$	35.7	Hasiguti type	21
		210 K		$\sim10^{-4}$	58 177 (two stages)	Hasiguti type	21
Au	99.999% Au (CW* 16% at 70 K)	130 K	4.0	4×10^{-3}	21.3	Hasiguti type	42
		190 K	4.0	2.2×10^{-2}	32.84	Hasiguti type	42
		210 K	4.0	6×10^{-3}	34.7	Hasiguti type	42
Au	99.999% Au (quenched) from 700°C)	160 K	~1	$\sim2\times10^{-3}$	68(?)	Associated with dislocations	43
		230 K		$\sim2\times10^{-3}$	—	Associated with dislocations	43
Au	99.999% Au (quenched from 800°C)	~290 K	~1	$\sim4\times10^{-3}$	—	Associated with dislocations	43
Au	99.999% (quenched from 1 000°C)	210 K	~1	$\sim4\times10^{-4}$	57.7	Stress induced reorientation of divacancies	44
		220 K	~1	—	—	Hasiguti type	44
Au	99.999 9% Au (quenched from 1000°C)	0°C	~10	7×10^{-4}–8×10^{-3}	62.7	Stress induced reorientation of divacancies	45
Au	99.99% Au (CW*, annealed at 600°C)	330°C	0.7	Depends on grain size	141.4	Grain boundary	46
Au	99.999 8% Au (CW* 36% annealed, 650–870°C°)	238°C	1.0	4.4×10^{-2}	144.3	Grain boundary	47
		404°C	1.0	3.2×10^{-2}	242.7	Associated with grain boundaries	47
Au	99.999 95% Au (annealed at 900°C)	~400°C	~1	$\sim10^{-1}$	435	Sliding at grain boundaries	48
Au–Ag–Zn	Au–42 At. % Ag–15 At. % Zn	260°C	0.7	0.11	146	Zener	49
Au–Cu	10 At. % Cu–90 At. % Cu	326–392°C	1.0	3.8×10^{-3}–0.57	114.6–165.3	Zener	50, 48
Au–Cu	10 At. % Cu–90 At. % Cu	552–753°C	1.0	0.14–0.76	201.7–342.3	Adsorption of solute atoms on grain boundaries	48
Au–Cu	10 At. % Cu–90 At. % Cu	175–250°C	1.0	5×10^{-2}–2×10^{-2}	—	Grain boundaries	48
Au–Cu	Au–25at% Cu (quenched)	490 K (quenched only)	~1			Point defects/order	267
	(quenched and annealed)	635 K (all)				Zener	
	(quenched and annealed)	760 K (all)				Grain boundary	
Au–Cu–Zn	42 At. % Cu–15 At. % Zn	380°C	0.5	0.14	—	Order–disorder peak	49
Au–Cu–Zn	21 At. % Cu–17 At. % Zn	300°C	0.5	0.50	—	Order–disorder peak	49
Au–Cu–Zn	63 At. % Cu–17 At. % Zn	340°C	0.5	2.6×10^{-2}	—	Zener	49
Au–Fe	5% Fe	365°C–535°C	~1	2.4×10^{-3}–1.5×10^{-2}	159–177.8	Zener Precipitation of Fe	51 51
Au–Fe	7% Fe	380°C–564°C	~1	1.9×10^{-2}–1.2×10^{-2}	159–177.8	Zener Precipitation of Fe	51 51

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Au–Fe	10% Fe–27% Fe	390°C	~1	3.5×10^{-2}–1.5×10^{-2}	151–151.9	Zener	51
Au–Ni	30 At. % Ni	397°C	1.0	—	182.0	Zener	52
Au–Ni	Au–30 At. % Ni (quenched)	~380°C	~0.5	$\sim10^{-1}$	88.3	Zener, modified by quenched–in vacancies	53
Au–Ni	7.7 At. % Ni–90.8 At. % Ni	397°C–652°C	1.0	—	182.0–251.0	Zener	52
Au–Zn	15 At. % Zn	250°C	0.7	4.2×10^{-2}	218	Zener	49
Au–Zn	Stoichiometric AuZn annealed	260°C–290°C	0.2–1	$\sim10^{-2}$	140	Concerned with short-range order (?)	54
Be		210 K	1.0	—	51.9	Bordoni type	55
		135°C	1.0	—	101.7	Solute atom/defect interaction	55
Be	98.6% Be (annealed)	213 K	~1	$\sim3\times10^{-4}$	50.2	Cold work induced line defect interaction (?)	56
		135°C	~1	$\sim5\times10^{-4}$	100	Solute interaction with lattice (?)	56
Be–Fe–O	Be–0.4 % Fe + interstitial impurities including oxygen	0.5°C	1.22	10^{-2}	63.6	Snoek type	57
Cd–Mg	Cd–29.3% Mg	20°C	0.75	0.26	80	Zener	58
Cd–Mg	5% Mg–30% Mg	20°C	1.0	0.29 max	79.5	Zener	59
Co	99.23% Co (0.69% N)	215 K (two peaks)	10^3	—	40.6	Bordoni type (?)	4
Co	99.23% Co (0.69% N) CW* at RT	263 K (two peaks)	10^3	—	51.0	Point defect/dislocation interaction	4
		297 K	10^3	—	36.8	Twin boundaries (?)	4
Co	99.999% Co (quenched)	410 K–600 K	10–5×10^2	$\sim2\times10^{-3}$	72.3	Movement of divacancies and dislocations	60
Co–C	Heated in C atmosphere at 1050°C and quenched	280°C	1–16×10^5	4×10^{-4}	159	Motion of C atom pairs in lattice	61
Co–Fe–Cr	Co–37.8% Fe–8.7% Cr. In magnetic field of 0.6×10^3 A/M	111°C	10^3	3×10^{-3}	—	Electron spin redistribution at Curie point	62
Co–Ni	Co–2% Ni	340°C	1.5–	$\sim2.5\times10^{-2}$	—	α–β phase	63
		430°C	1.8×10^4	$\sim2.8\times10^{-2}$	—	transformation	63
Co–Ni	Co–23% Ni	150°C	1.5–	$\sim2.9\times10^{-2}$	—	α–β phase	63
		310°C	1.8×10^4	$\sim3.1\times10^{-2}$	—	transformation	63
Co–Ni–Cr–W	Co–22wt% Ni–22wt% Cr–14wt% W (wrought alloy)	~370°C				Snoek effect (C–C pairs)	259
Cr	99.8% Cr	38°C	—	2×10^{-3}	—	Electron spin redistribution at Neel temp. (40°C)	64
Cr–N	Cr–0.004 5% N	160°C	1.0	1.5×10^{-3}	101.7	Snoek type	65
Cr–N	35 ppm N (quenched from 83°C)	~36°C	3	$\sim4\times10^{-4}$	115.1	Magneto-mechanical damping	66
Cr–N	(Annealed in NH_3 at 1150°C for 48 h)	155°C	1	up to 2.2×10^{-3}	85.8	Snoek type	67
Cr–Re–N	Cr–35% Re (quenched from 1000°C in NH_3 atmosphere)	130°C	1	$\sim10^{-3}$	89.1	Snoek type	68
		190°C	1	$\sim10^{-3}$	126.4	Snoek type	68
Cu	99.999% Cu (CW* at 77 K	—	~1	—	4.34	Niblett–Wilks type	69
		—	~1	—	11.6	Bordoni type	69

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Cu	99.999% Cu (single crystal) CW* 5% at 77 K	38 K	1.09×10^4	2×10^{-3}	4.2	Bordoni type	19, 41, 70, 71,
		79 K	1.09×10^4	4×10^{-3}	11.7	Bordoni type	19, 41, 70, 71
Cu	99.999% Cu (single crystal ⟨100⟩ orientation)	80 °C	13	34×10^{-4}	—	Bordoni type	238
Cu	99.999% Cu (single crystal ⟨110⟩ orientation)	70 °C	13	11.4×10^{-4}	—	Bordoni type	238
Cu	Electrolytic Cu (Fatigued, 4×10^5 cycles)	140 K	0.3	$\sim 4 \times 10^{-4}$	—	Dislocation–divacancies interaction	72
		225 K	0.3	$\sim 4 \times 10^{-4}$	—	Dislocation–vacancies interaction	72
		240 K	0.3	$\sim 2 \times 10^{-4}$	—	Dislocation–interstitials interaction	72
		165 K	0.3	$\sim 1 \times 10^{-4}$	—	Dislocation–interstitials interaction	72
Cu	99.999% Cu (deformed 2.5% quenched in liquid He)	30 K	6×10^2	$\sim 10^{-3}$	—	Niblett–Wilks type	73
		70 K	6×10^2	$\sim 3 \times 10^{-3}$	—	Bordoni type	73
		190 K	6×10^2	$\sim 10^{-4}$	—	Hasiguti type	73
Cu	99.999% Cu (CW* 5% at 77 K)	148 K	1.0	4×10^{-5}	31.0	Point defect, dislocation interaction	74
		170 K	1.0	1.2×10^{-2}	33.9	Point defect, dislocation interaction	74
		238 K	1.0	1×10^{-2}	41.4	Rotation of split interstitials (?)	74 75
Cu	99.999% Cu (annealed at 500 °C for 4 h)	215 °C	1.0	2.11×10^{-2}	157	Grain boundary	
Cu	99.99% Cu (area reduced 47%, annealed at 600 °C for 2 h)	216 °C	1.17	1.65×10^{-2}	132	Grain boundary	5
Cu	99.999 9% Cu	416 °C	~1	~0.2	435	Sliding at grain boundaries	48, 76
		735 °C	~1	~0.2	169.5	Sliding at grain boundaries	76
Cu	99.999% Cu	300 °C	5.0	4×10^{-2}	156.9	Grain boundary	75
Cu–Ag	Cu–0.71% Ag	550 °C	1	—	154.7	Grain boundary	237
Cu–Ag	Cu–0.1 At. % Ag CW* 5%	223 K	5×10^3	2.6×10^{-4}	—	Dislocation/silver atom/point defect interaction	250
		283 K	5×10^3	2.5×10^{-4}	—		
Cu–Al	2% Al–10% Al (Deformed 3% at RT)	145 K	1.5×10^7	—	~24	Bordoni type	77
Cu–Al	Cu–15wt% Al (cold worked)	−60 °C	~2	0.04			308
Cu–Al	Cu–16.8 At. % Al	360 °C	0.66	7×10^{-3}	174.9	Zener	78
Cu–Al–Ni	Cu–13wt% Al –7.9wt% Ni (solution-treated at 1223 K and cooled at various rates)	323 K at all rates	~520–680			Twin boundary relaxation of gamma-mart.	281
		Others at high rates					
Cu–Au	Cu–25at% Au (annealed)	680 K	~1			Zener	266
		800 K				Grain boundary	
Cu–Au	Cu–1.5at% Au (cold worked and annealed at100 °C)	−50 °C	~1			Interaction between dislocations and Au clusters	310

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Cu–Co	(Aged at 575 °C for 3 min)	230 °C	1	7×10^{-4} (depends on ageing)	184.9	Grain boundary	75
Cu–Ga	Cu–16 At. % Ga	330 °C	1.0	2×10^{-2}	—	Zener	33
Cu–Fe	0.5% Fe–10% Fe	320 °C–350 °C	~1	Depends on grain size	159	Grain boundary	79
		480 °C–550 °C	~1	Depends on grain size	209	Connected with precipitation of Fe on Cu grains	79
Cu–Fe	Up to 1.5% Fe (Quenched from 820 °C)	800 °C–850 °C	~1	$\sim 10^{-1}$	~125	Connected with ageing of alloy	80
Cu–Ni	25% Ni–75% Ni (Quenched from 720 °C to 240 °C)	34 K	~1	—	79.9	Associated with precipitation	81
		150 K	~1	—	111.3	Associated with precipitation	81
Cu–Ni	Cu–3% Ni (Annealed at 1 100 °C)	~580 °C	~1	2.1×10^{-3}	151	Zener	82
Cu–Ni	Cu–45% Ni (Reduced by 90% at RT)	~600 °C	~1	$\sim 2 \times 10^{-2}$	—	Associated with recrystallization (?)	83
		~800 °C	~1	$\sim 5 \times 10^{-2}$	208	Associated with dislocations	83
Cu–Ni	5.6 At. % Ni–94.9 At. % Ni	590–726 °C	~1	0.129–0.112	368–264	Grain boundary	84
Cu–Ni–Zn	20 At. % Zn–10 At. % Ni	381 °C	1	5.3×10^{-3}	197	Zener	85
Cu–Ni–Zn	$Cu_2Ni_{1.15}Zn_{0.92}$ single crystal	76 K	6.9	3×10^{-2}	—	Zener	244
		71 K	6.9	1.2×10^{-2}	—	Ordering	244
Cu–Pd	0.01% Pd–0.3% Pd	30–150 K	5×10^6	$10^{-4} - 10^{-3}$	—	Overdamped resonance of dislocations	86
Cu–Pt	0.01% Pt–0.3% Pd	30–150 K	5×10^6	$10^{-4} - 10^{-3}$	—	Overdamped resonance of dislocations	86
Cu–Si	Cu + 5.09 wt. % Si	200 °C	3	7.5×10^{-3}	118	Precipitation of K^1	248
Cu–Si	Cu–5.09wt% Si (precipitation treated)	200 °C	3		28 kcal mol^{-1}	Relaxation at ppt. interfaces in stacking faults	306
		366 °C	3		1.74 eV	Grain boundary	
Cu–Sn	3% Sn–9% Sn	490–500 °C	1.8	0.14–0.152	151–205	Grain boundary	87
Cu–Zn	(α) Cu–31% Zn	R.T.	6×10^3	1.8×10^{-4}	—	Thermoelastic	88
Cu–Zn	10% Zn–30% Zn	290–350 °C	0.7	$\left(\frac{\text{At. conc } Zn}{4}\right)$	159–178	Zener	12
Cu–Zn	17.6 At. % Zn–29.4 At. % Zn	657–614 K	1.3	3.5×10^{-3}–9.2×10^{-3}	182.0–161.1	Zener	89
Cu–Zn	Cu–30% Zn	425 °C	0.5	0.12	172(?)	Grain boundary	90
Cu–Zn	(β) Cu–45 At. % Zn (Quenched from 400 °C)	70 °C	0.9	2.6×10^{-3}	69.5	Diffusion of Zn accelerated by vacancies	91
Cu–Zn	(β) Cu–45 At. % Zn	177 °C	0.9	1.4×10^{-3}	130	Stress induced reorientation of Cu atom pairs	91 91
Cu–Zn	(α–β) Cu–43 At. % Zn	285 °C	0.9	8×10^{-3}	159	Stress relaxation at β–α interfaces	91
Cu–Zn	(β–γ) Cu–50 At. % Zn	190 °C	0.9	2.2×10^{-3}	130	Stress relaxation at β–γ interfaces	91
Cu–Zn–Al	77% Cu–89% Cu 5% Zn–20% Zn 2% Al–8% Al	623–672 K	~1	2×10^{-3}–8.5×10^{-3}	—	Zener	92

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Cu–Zn–Al	Cu–29.5% Zn–2.4% Al	593 K	1	3.5×10^{-2}	150.6	Zener	93
Cu–Zn–Al	Cu–17.0% Zn–9.0% Al	615 K	1	3.27×10^{-2}	163.2	Zener	93
Fe	(Re-electrolytic) (CW* 5% at RT, in magnetic field of 7.5×10^4 A/m)	~50 K	10^5	$\sim 1.5 \times 10^{-3}$	—	Associated with motion of kinks in dislocations	94
Fe	Armco (CW* at RT)	198 K	10^3	—	44.4	Point defect/dislocation interaction	4
Fe	Armco (CW* at RT)	230 K	10^3	—	54.8	Point defect/dislocation interaction	4
Fe	CW* 40% at RT	275 °C	2.9	1.55×10^{-3}	174	Köster type	95
Fe	99.98% Fe ($< 5 \times 10^{-5}$ CN)	526 °C	1.03	Depends on grain size	192	Grain boundary	96
Fe	Fe pure (R ratio 1600) irradiated	110 K	1.4	4×10^{-4}	—	Magnetic relaxation of point defects	246
	2×10^{18} cm^{-2} at 20 K	128 K	1.4	13×10^{-4}	—	Magnetic relaxation of point defects	246
		155 K	1.4	55×10^{-4}	—	Relaxation of self-interstitials	246
Fe–Al	Fe–40 At. % Al	180 °C	0.6	3.5×10^{-3}	121	Movement of Al within tetrahedral lattice	97
		320 °C	0.6	6×10^{-3}	163	Movement of Al within tetrahedral lattice	
Fe–Al	Fe–40 At. % Al	440 °C	0.6	1×10^{-3}	184	Movement of Al	97
		550 °C	0.6	5×10^{-4}	—	within tetrahedral lattice Zener	
Fe–Al	Fe–17 At. % Al	520 °C	1.3	1×10^{-2}	234	Zener	98
Fe–Al–C	Fe–19.3 At. % Al–0.01% C (Quenched from 720 °C, aged)	130 °C	1.4	$\sim 1 \times 10^{-3}$	99.6	Stress induced diffusion of C in ordered Fe_3Al lattice	99
		168 °C	1.4	$\sim 5 \times 10^{-3}$	—	(?)	
Fe–Al–C	Fe–0.7 At. % Al–0.01% C	41 °C	1.2	$\sim 10^{-2}$	—	Snoek type	99
Fe–Al–C	Fe–9 At. % Al–0.01% C	~100 °C	1.2	$\sim 3 \times 10^{-3}$	—	(?)	99
Fe–B	Fe–0.05% B	79 °C	14.0	—	63	Snoek type	100
Fe–B	Fe–50 ppm B (C impurities)	260 K	~1	$\sim 10^{-4}$	54	Snoek type due to B	101
		50 °C		$\sim 3 \times 10^{-3}$	—	Snoek type due to C	
Fe–C	Fe–0.02% C	27 °C	0.27	2×10^{-2}	84.1	Snoek type	102
Fe–C	Fe–0.4% C (Martensite). (Quenched from 850 °C, tempered at 300 °C for 1 h)	~200 °C	~1	$\sim 10^{-2}$	84.5	Associated with dislocations	103
Fe–C	Fe–0.02% C (Quenched from 700 °C, CW* 52%, aged)	210 °C	1	$\sim 5 \times 10^{-3}$	—	Dislocation movement between pinning points (precipitates)	104
Fe–C	Fe–0.01% C (CW* 25%)	235 °C	2.20	8×10^{-3}	138	Köster peak	105
Fe–C	—	353 °C	6.65×10^6	$\sim 3 \times 10^{-3}$	80.17	Snoek type	106
Fe–C	Fe–0.022% C	520 °C	1.0	Depends on grain size	347	Grain boundary	107
Fe–Co–Cr	Fe–54% Co–10% Cr	380 K	6×10^3	$\sim 5 \times 10^{-4}$	—	Macro-eddy current peak	108
Fe–Cr	1.2% Cr–43% Cr	526 °C–683 °C	1.0	3×10^{-3}–10^{-2}	215.5–296.2	Grain boundary	109
Fe–Cr	Fe–16% Cr	661 °C	~1	3.18×10^{-2}	233	Grain boundary	110

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Fe–Cr	Fe–22.5% Cr	662°C	~1	0.55×10^{-2}	222	Grain boundary	110
Fe–Cr	Fe–22.5% Cr	~560°C	~1	1.1×10^{-2}	222	Zener	111
Fe–Cr	Fe–17wt% Cr–Deuterium (cold worked)	~250 K	300–2000			Snoek	264
Fe–Cr–Al–RE	Fe–13at% Cr–6at% Al–2at% Mo–0.05at% Ce	450°C; 624°C; 690°C	0.67, 0.59; 0.55		–; 3.3 eV; 4.0 eV	Zener (Fe–Cr pairs); solute G.B. peak of Fe–Cr; ditto Fe–RE	294
	Fe–27at% Cr–7at% Al–2at% Mo–0.056at% Ce	523°C; 663°C; 713°C	0.61; 0.56; 0.51		–; 3.6 eV; 4.0 eV – ;		
	Fe–23at% Cr–6at% Al–0.065at% Y	529°C; 632°C; 690°C			3.3 eV; 3.9 eV		
Fe–Cr–C	Fe–(1.2% Cr–5.2% Cr)–C (Quenched from 750°C)	~320 K	~1	$\sim 10^{-2}$	75.31–82.72	Snoek type	112
Fe–Cr–N	Fe–4.2% Cr–N	(Several peaks) 266 K–339 K	~1	Up to 2.3×10^{-3}	67.8–92.0	Motion of N atoms in various environments	113
Fe–Cr–N	Fe–16.6wt% Cr–130/200 ppm N (quenched from 1000°C)	270/250°C	~0.9			Snoek	290
	Fe–16.6wt% Cr–480/580 ppm N	Peak broadened				Associated with martensitic phase	
Fe–Cr–Ni	304L stainless steel (cold worked)	335–340 K	~1000		0.6 eV (other peaks at 0.4, 0.4 eV)	? but height depends on amount of cold work	289
Fe–Cr–Ni (–H)	304, 316 and 310S (+ ~10at% H) (electrolytically charged with H)	230 K 300 K	1.5 200–2000		49.0 49.0	Stress-induced ordering of H pairs	303
Fe–Cr–Ni	Sus 310S, 316 and 304 (H charged only)	300 K	~550			H–H Snoek	280
	(plus cold-work)	300 K + 330 K (CW) and 230 K (H + CW)				Bordoni H-lattice defects	
Fe–Cr–Ni	304L stainless steel (cold-worked)	325 and 360 K	~500			Gamma phase and alpha martensite resp.	286
αFe–H	Fe(<0.1 At. % H)	30 K	1.0	8×10^{-4}	—	Snoek type	114
αFe–H	Fe(<0.1 At. % H) (CW* 0.5%)	116 K	1.0	1.6×10^{-3}	—	Köster type	114
Fe–H	Fe–H (aged at 60°C for 5 h)	~150 K ~180 K	8×10^4 8×10^4	$\sim 2 \times 10^{-4}$ $\sim 6.5 \times 10^{-4}$	— —	Köster type Köster type	115 115
Fe (–H)	Pure Fe electrolytically charged with H (deformed before charging)	130 K; 170 K; 330 K	1		0.22; 0.35; ?	Peaks at 130 and 170 K due to interaction between dislocations and aggregated H; thermally activated kink-pair on screw disloc.	296
αFe–D	(CW* 0.5%)	35 K 120 K	1.0 1.0	8×10^{-4}– 10^{-3}	— —	Snoek type Köster type	114 114
Fe–Mn–C	Fe–18.5% Mn–0.7% C	250°C	2.0	1.1×10^{-2}	146	Diffusion of C in fcc Fe–Mn	116
Fe–Mn–C	Fe–15.5% Mn–0.35% C	285°C	1.01	1.6×10^{-3}	155	Stress induced ordering of C atoms	117

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Fe–Mn–N	Fe–2% Mn–N (Quenched from 950°C)	(Several peaks) 267 K–337 K	~1	Up to 1.5×10^{-2}	66.1–91.6	Motion of N atoms in various environments	113
Fe–Mn–N	Fe–1.6% Mn–N (Heated at 590°C in NH_3)	7°C	1	$\sim 4 \times 10^{-3}$	69.0	Snoek type in complex lattice	118
		23°C	1	$\sim 5 \times 10^{-4}$	77.4	Snoek type in Fe	
		34.5°C	1	$\sim 2 \times 10^{-3}$	81.6	N atoms jumping from Fe–Mn sites to Fe–Fe sites	
Fe–Mn–N	Fe–2% Mn–0.01% N	135°C	~1	$\sim 10^{-3}$	—	—	119
αFe–N	—	22°C	0.89	$\left(\frac{\text{wt. \%N}}{0.63}\right)$	77.8	Snoek type	120
αFe–N	Fe–0.01% N (CW* 25%)	235°C	2.35	1.3×10^{-2}	138	Köster type	105
Fe–N	Fe–0.05% N (Quenched from 580°C, area reduced 21%)	250°C	1	$\sim 5 \times 10^{-3}$	—	Dislocation movement between pinning points (precipitates)	104
Fe–N	—	326°C	6.65×10^6	$\sim 2 \times 10^{-3}$	76.78	Snoek type	106
Fe–N	Fe–0.018% N	510°C	1.0	Depends on grain size	315.9	Grain boundary	107
Fe–Ni	Fe–31.5% Ni	415 K	6×10^3	$\sim 10^{-4}$	—	Macro-eddy current peak	108
Fe–Ni	Fe–54wt% Ni (hydrogen-charged)	260 K (sub-peak 225 K)	500		43.2	Snoek	275
	Fe–72.8wt% Ni (hydrogen-charged)	240 K (sub-peak 265 K)	500		42.3	Snoek	
Fe–Ni	Fe–5% Ni C impurities	40°C	1.2	2×10^{-3}	—	Snoek type	95
	(CW* 40% at RT)	215°C	2.9	1.15×10^{-3}	135	Köster type	95
Fe–Ni	Fe–4% Ni (CW*,	500°C	1.0	0.24	213–259	Grain boundary	121
	annealed)	750°C	1.0	0.50	247–289	(?)	121
Fe–Ni	Fe–36wt% Ni (Invar)–H	250 K	700		43	Snoek	268
	Fe–36wt% Ni (Invar)–D	253 K	700				
Fe–Ni–Cr	Fe–26.0% Ni–21.4% Cr	629°C	~1	Depends on grain size	350	Grain boundary	122
	(Annealed from	692°C	~1		294	Grain boundary	122
	1 000°C)	769°C	~1		296	Grain boundary	122
Ni–Cr steel	18CrNiWA steel (continuous cooling)	400–430°C	0.7			Bainitic transformation	260
	18CrNiWA steel (continuous cooling)	320°C					
	18CrNiWA steel (after decarburizing)	600°C					
Fe–Ni–N	Fe–2.29% Ni–N	24.5°C	1.05	1.009×10^{-2}	77.8	Snoek type due to N	113
		40.5°C	1.05	8.8×10^{-4}	84.1	Snoek type due to C	113
Fe–Ni–Cr–Mn	Fe–19wt% Cr–9wt% Ni (hydrogen-charged)	~300 K	700			Snoek	269
	Fe–17wt% Cr–4wt% Ni–6wt% Mn (hydrogen-charged)	~310 K	700			Snoek	
	Fe–15wt% Cr–12wt% Mn (hydrogen-charged)	~310 K	700			Snoek	
Fe–P	Fe–0.37% C–0.03% P	40°C	1.1	3.8×10^{-3}	146	Impurity peak due to P	123
Fe–Ni–P–B	Fe–40at% Ni–14at% P–6at% B (amorphous, cold-worked and H charged)	204 K (mag. after eff. 163 K)				Both peaks rise after ageing at 340 K	278

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Fe–Si–N	Fe–2.83% Si–0.05% N	22.5°C	1.26	—	75.3	Snoek type	124
		37°C	1.26	—	50.2	N atom jump in vicinity of Fe–Si sites	124
		62°C	1.26	—	—	N atom jump in vicinity of nitride SiN	124
Fe–Ti–N	Fe–0.15% Ti–0.06% N	~120°C	~1	$\sim 10^{-3}$	105	Interstitial N interacting with Ti	125
		~227°C	~1	$\sim 10^{-3}$	130	Interstitial N interacting with Ti	125
Fe–V	Fe–18% V	625°C	0.73	1.6×10^{-2}	355.6	Zener	126
Fe–V–C	Fe–0.62% V (Carburized at 800°C for 4 h, quenched)	33°C	0.95	3.1×10^{-3}	50	Snoek type due to C	127
		82°C	0.95	6.6×10^{-3}	46	C atom jumps associated with Fe–V sites	127
Fe–V–C	Fe–5.15% V–240 ppm C. (Quenched from 900°C)	77°C	451	9.8×10^{-5}	81.0	Interaction between V and C atoms in solution	128
		109°C	451	6.1×10^{-5}	83.9	Snoek type	
Fe–V–N	Fe–0.51 At. % V–0.58 At. % N	21.5°C	0.77	2×10^{-2}	79.5	Snoek type	129
		84°C	0.77	1.4×10^{-2}	—	N atom jump in vicinity of nitride VN	129
Fe–V–N	Fe–0.62% V–N. (In NH_3, 900°C for 14 h). (C impurities)	24°C	1	2×10^{-2}	75	Snoek type due to N	127
		35°C	1	3×10^{-3}	85.8	Snoek type due to C	127
		84°C	1	3×10^{-3}	75.3	N atom jumps associated with Fe–V sites	127
Ga–As	GaAs (Compound) [111] (with damaged surfaces)	229 K	3.7×10^{4}	4.0×10^{-5}	40.5	Associated with dislocations on surface	130
Ga–Sb	GaSb (Compound) (With damaged surfaces) [100]	225 K	9.46×10^{4}	2.0×10^{-5}	37.6	Associated with dislocations on surface	130
Gd	(Annealed at 900°C for 2 h)	190 K	~1	$\sim 10^{-3}$	—	Micro-eddy current damping	131
		240 K	~1	$\sim 3 \times 10^{-3}$	—	Motion of 90° domain boundaries	131
Ge	Surface damaged by polishing [100]	150 K	$\sim 2 \times 10^{3}$	$\sim 2 \times 10^{-5}$	29	Associated with dislocations	132
	[111]	205 K	$\sim 2 \times 10^{-3}$	$\sim 2 \times 10^{-5}$	29	Associated with dislocations	132
Ge		209 K	3×10^{3}	1.3×10^{-7}	52.1	Associated with dislocations	133
Ge	Surface damaged [111]	228 K	5.49×10^{4}	4.1×10^{-5}	36.6	Associated with dislocations on surface	130
Ge	Zone-refined. (Strained up to 12.2%)	35°C	$\sim 10^{3}$	$\sim 1.2 \times 10^{-4}$	60	Motion of geometrical kinks over jogs on dislocations	134
Ge	Zone-refined. (Strained up to 12.2%, annealed at 550°C)	180°C	$\sim 10^{3}$	$\sim 10^{-5}$	82	Motion of dislocations in region of surface	134
Ge	Single crystal	395°C	10^{5}	1.8×10^{-5}	77.4	Electronic relaxation	135
		770°C	10^{5}	4×10^{-7}	173.6	Impurity peak (?)	135
Ge	(CW* at 800°C)	~450°C	~1	$\sim 10^{-4}$	~175	Bordoni type	136
Ge–Sb	Ge, doped with Sb	~80°C	2.5×10^{3}	$\sim 3 \times 10^{-5}$	14.5	Kink motion	137
	(CW* to produce screw dislocations)	~180°C	2.5×10^{3}	$\sim 5 \times 10^{-5}$	24.1	Kink motion	137
		~300°C	2.5×10^{3}	$\sim 1.5 \times 10^{-4}$	106	Kink motion	137

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Ge–Sb	Ge, doped with Sb (CW* to produce Edse dislocations)	~290 °C	2.5×10^3	$\sim 3 \times 10^{-4}$	106	Kink/point defect interaction	137
Ge–Sb	Ge, doped with Sb annealed	~310 °C	2.5×10^3	$\sim 10^{-4}$	106	Dislocation/point defect interaction	137
Ge–Sb	Ge–4×10^{17} atoms Sb/ millilitre	216 K	4.1×10^3	2.4×10^{-7}	55.0	Involving dislocations	133
αHf–O	—	490 °C	0.95	—	—	O atom diffusion in vicinity of Zr impurity	138
Hg–Te	Mercury telluride	170–260 K	10^7–3×10^9	—	9.07	Bordoni type	139
In–Sb	InSb compound [111] with damaged surfaces	222 K	5.65×10^4	5.1×10^{-5}	32.8	Associated with dislocations on surface	130
In–Sb	InSb compound with surface damage [211]	231 K	3.54×10^4	3.8×10^{-5}	41.5	Associated with dislocations on surface	130
In–Tl	In–10 At. % Tl	270 K	2	$\sim 5 \times 10^{-4}$	67.4	Zener	140
		390 K	2	$\sim 2 \times 10^{-3}$	111.7	Reorientation of lattice with respect to grain boundaries	140
In–Tl	In–10 At. % Tl	273 K	~1	—	67	Zener	141
		368 K	~1	0.5	29	Motion of twin boundaries	141
Ir	99.96% Ir (Annealed at 1 720 °C)	1 450 °C	2.0	7.5×10^{-2}	339	Grain boundary	142
K	(Nominal purity) annealed at RT cooled to 120 K	160 K	5×10^3	$\sim 10^{-3}$	~125	Stress induced change in size or shape of precipitates	143
K–Rb	20 At. % Rb–	193 K	3.7×10^3	2.25×10^{-4}	41.42–40.38	Zener	144
	50 At. % Rb	179.5 K	13×10^3	1.9×10^{-3}			
Li–Mg	Li–57 At. % Mg (single crystal)	127 °C	1.38×10^3	1.7×10^{-2}	90.0	Zener	145
Lu–H (–D)	Lu–<20at% H (annealed)	215–225 K				H–H Snoek	279
	Lu<290at% H+D (deformed only)	250–260 K, 350 K				D-dislocation, dislocation/dislocation	
Mg	Mg–Small amounts of Al, Zn, Cd, Tl, In	Peaks from 0–300 K	1.5×10^{-2} — 0.75	Complex spectrum	—	Dislocation/ dislocation interaction	146
Mg	High purity (99.9999wt% Mg) (deformed at 10 K)	40 K; 80 K	1			Bordoni, stable on annealing	304
		105 K; 220 K				Hasiguti, removed by thermal cycling up to 300 K	
Mg	99.996% Mg	20 K	$\sim 10^4$	$\sim 4 \times 10^{-4}$	—	Associated with grain boundaries (?)	147
		40–240 K	$\sim 10^4$	$\sim 10^{-3}$	—	Dislocation movement in (0001) slip system	147
Mg	99.992% Mg (CW*)	20 K	4×10^4	3×10^{-3}	—	Bordoni type (?)	148, 71
		100 K (very broad)	4×10^4	—	—	Bordoni type	71
Mg	—	37 K	1.5×10^7	—	0.9	Dislocation motion in basal plane	149
		106.5 K	1.5×10^7	—	8.7	Dislocation motion in non-basal plane	149
		155.5 K	1.5×10^7	—	40.5	?	149

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Mg	99.99% Mg (CW* at RT)	180 K	10^5	—	28.9	Point defect/dislocation interaction	4
		225 K	10^3	—	42.3	Point defect/dislocation interaction	4
Mg	99.97% Mg	220°C	0.46	8×10^{-2}	—	Grain boundary	26
Mg	99.9999% Mg	40 K	1–2	3×10^{-3}	—	Bordoni (B1)	242
	1–2% CW at 10 K	80 K	1–2	1×10^{-2}	—	Bordoni (B2)	242
Mg	High purity	15 K	~1			Pi sub 1	274
		40 K				Bordoni 1	
		80 K				Bordoni 2	
		105 K				Hasiguti 1	
		220 K				Hasiguti 2	
		420 K				P sub a	
Mg–Li	Mg–1.88% Li	51 K	1.5×10^7	—	1.74	Dislocation motion in basal plane	149
Mg–Li		99.5 K	1.5×10^7	—	9.6	Dislocation motion in non-basal plane	149
		154.5 K	1.5×10^7	—	126	?	149
Mg–N	Mg–0.0048% N	46 K	1.5×10^7	—	1.0	Dislocation motion in basal plane	149
		116 K	1.5×10^7	—	22	Dislocation motion in non-basal plane	149
		157 K	1.5×10^7	—	35	?	149
Mn–Cu	Mn–12% Cu (Quenched from 925°C)	268 K	7×10^2	3.6×10^{-4}	—	Stress relaxation across twin boundaries	150
Mo	Zone refined (CW* 5% at RT)	80 K	5	3×10^{-3}	17.36	Bordoni type	151
		240 K	5	2.8×10^{-3}	44.4	Bordoni type	151
		285 K	5	2.8×10^{-3}	44.4	Bordoni type	151
Mo	High purity (deformation at high temp.)	130 K	25×10^3			Kink/pair formation and migration on disloc.	288
	(deformation at low temp.)	100 K; 140–200 K	25×10^3			Kink/pair on non-screw disloc.; kink migration on screw disloc.	
	(H anneal + deformation and low temp. anneal)	370 K	25×10^3			Interaction of H with screw dislocations	
Mo	99.9% Mo (CW* 30% at RT)	~110 K	$\sim 10^3$	$\sim 2 \times 10^{-3}$	—	Associated with dislocations	152
Mo	99.9993% Mo (Deformed 50% at 450 K)	~140 K	$2–2 \times 10^7$	$\sim 10^{-2}$	—	Associated with dislocations	153
Mo	99.995% Mo polycrystalline (CW*)	145 K	1.9×10^3	$\sim 10^{-3}$	—	Dislocation type	154
Mo	High purity Mo R/Ratio 7 500–8 000	~140 K	500	3×10^{-3}	—	Dislocation motion	245
Mo	Zone refined (CW* 5% at RT)	300 K	0.4	1.4×10^{-2}	—	Köster type	155
Mo	Impure	~100°C	~1	$\sim 3.5 \times 10^{-3}$	109	Snoek type due to N	156
		~220°C	~1	$\sim 7.2 \times 10^{-3}$	134	Snoek type due to O	156
		~310°C	~1	$\sim 5.0 \times 10^{-3}$	163	Snoek type due to C	156
Mo	Zone refined (Annealed at 2 300°C for 20 min)	200–225°C	~1	$\sim 2 \times 10^{-3}$	126–134	Dislocation type	157
Mo	Zone refined single crystal (annealed at 1 800°C for 40 min)	~800°C	~1	$\sim 2 \times 10^{-2}$	272	Short range interaction between dislocations and C atom interstitials	158
Mo		820–870°C	1.0	—	—	Grain boundary	157
Mo	Commercial	1 000–1 150°C	~1	$\sim 6 \times 10^{-2}$	372	Grain boundary	159
		1 300–1 600°C	~1	~0.13	54	Recrystallization peak	159

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Mo	99.98% Mo (Annealed at 1340°C)	1050°C	1.3	3.3×10^{-2}	389	Grain boundary	142
Mo	Zone refined, recrystallised, CW* RT, annealed at 1900°C for 90 min	~1200°C	5	$\sim 10^{-2}$	—	Grain boundary	158
Mo–C	Mo–0.0034% C	225°C	1.71	4.4×10^{-3}	126–134	Snoek type	157
Mo–N	Mo wire (nitrided at 2400K)	392K; 498K	~1			Dislocation interaction; Snoek	291
Nb	Zone refined (CW* 5% at RT)	130 K (α peaks)	8	6×10^{-4}	23.0	Bordoni type	151, 163, 164
		240 K (β peaks)	7.8	2.1×10^{-3}	45.2	Bordoni type	151, 163
Nb	99% Nb. (CW* 5%, annealed at 70°C for 2h)	190 K	~1	$\sim 10^{-4}$	—	Associated with point defect complexes	164
		200 K	~1	$\sim 10^{-3}$	~95	Associated with point defect complexes	164
		220 K	~1	$\sim 10^{-4}$	—	?	164
Nb	99.998% Nb (CW* 50% at RT)	220 K	$2–2 \times 10^{7}$	$\sim 7.5 \times 10^{-3}$	—	Dislocation damping	153, 165, 166
Nb	Nb–0.005% N–0.005% O (Zone refined)	~580°C	8×10^{3}	$\sim 7.8 \times 10^{-3}$	—	Snoek type due to N	167
		~380°C	8×10^{3}	$\sim 3.5 \times 10^{-3}$	—	Snoek type due to O	167
		~470°C	8×10^{3}	$\sim 1 \times 10^{-3}$	—		167
Nb	(CW*)	~630°C	8	—	—	Relaxation of ordered cluster of interstitials near dislocations	168
Nb–Al	Nb–0.29% Al (0.004% C, 0.003% N, 0.029% O) (Annealed)	152°C	1	$\sim 9 \times 10^{-3}$	—	Snoek type due to N	169
		283°C	1	$\sim 1 \times 10^{-3}$	—	Snoek type due to O	169
Nb–Al	Nb–0.29% Al (0.004% C, 0.003% N, >0.029% O) (CW*)	410°C	1	$\sim 1 \times 10^{-3}$	—	Dislocation/solute interaction	169
Nb–C	Nb–0.014% C	259°C	0.57	4×10^{-3}	139.3	Snoek type	170, 171
Nb	High purity single crystal + 180 at ppm H. CW at 320 K	270 K	1.3×10^{3}	3.0×10^{-2}	—	Snoek–Köster type	239
Nb	Nb single crystal R. ratio 2500	α_1 143 K	0.5	10×10^{-3}	29.7	Formation of kink-pairs in non-screw dislocation	249
		α_2 121 K	0.5	6×10^{-3}	19.8	Kink diffusion in screw dislocation	249
Nb–Mo	1.3% Mo–16% Mo (CW* 30% at RT)	180–220 K	$2–2 \times 10^{7}$	5×10^{-4}–1×10^{-4}	24.1	Type of Bordoni mechanism	153, 166
Nb	99.97% Nb(CW*) (Superconducting type)	3.24 K	8×10^{4}	$\sim 2 \times 10^{-6}$	0.18	Motion of dislocations	160
	(Normal type)	2.08 K	8×10^{4}	$\sim 4 \times 10^{-6}$	0.15	Motion of dislocations	160
Nb	Zone refined (CW* 5% at RT)	11–19 K (Broad)	8.8	10^{-4}	—	Bordoni type (?)	161
Nb	99.9% Nb (CW*)	~30 K	2×10^{4}–1×10^{5}	$\sim 2 \times 10^{-4}$	1.6	Motion of dislocations	162
		~180 K	2×10^{4}–1×10^{5}	$\sim 1 \times 10^{-4}$	24.1	Interaction of dislocations and impurity atoms	162
Nb	High purity single crystal CW at 320 K	190 K	1.3×10^{3}	1.2×10^{-2}	—	Motion of dislocation	239

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Nb–Mo–O	Nb–5.3 At. % Mo–0.16 At. % O (Homogenized at 1200°C for 15 min)	167°C	0.6	$\sim 10^{-2}$	—	Snoek type	172
Nb–N	Nb–0.018% N	274°C	0.55	1.1×10^{-2}	145.6	Snoek type	170, 171
Nb–N	Nb–0.066% N (CW* 10%)	500°C	0.31	2.4×10^{-2}	201	Köster type	173
Nb–N–T	Nb–0.50at% N–0.3at% T (Tritium)	57 K; 85 K	~1			N/H pairs; N/T pairs	297
Nb (–O)	'Pure' nobium (wire)	300–350 K	~1		0.6 eV	Extrinisic double-kink/O atoms	287
		350–360 K			0.8 eV	Intrinsic double-kink on screw disloc.	
		~500 K				Thermal unpinning of screw disloc. from O	
Nb–O	Nb–0.18 At. % O	152°C	0.6	$\sim 10^{-2}$	—	Snoek type	172
Nb–O	Nb–0.026% O	168°C	2.13	1.6×10^{-2}	114.2	Snoek type	174, 171
Nb–O	Nb–50 to 1000 ppm O (worked polycrystals)	543–575 K	1		2.00–2.06 eV		270
		692–726 K	1		1.68–1.81 eV		
		618 K (low O)	1		1.49 eV		
		621 K (high O)	1		1.50 eV		
Nb–O–N	Nb–1.2 At. % O–0.11 At. % N	420 K	~1	$\sim 5 \times 10^{-3}$	—	Segregation of O atoms to dislocations	175
	(CW* 34%)	500 K	~1	$\sim 1 \times 10^{-3}$	—	Segregation of N atoms to dislocations	175
Nb–O–T	Nb–0.56at% O–0.3at% T (tritium)	50 K; 80 K	~1			O/H pairs; O/T pairs	297
Nb (–Ta)	Nb–0.03wt% Ta (70 ppm O, 30 ppm N) (neutron irradiated and annealed 1.25 mm wires)	470 K				O plus irradiation defects	283
		670 K				N plus irradiation defects	
Nb–Ti	Nb–48% Ti	100°C	0.6	$\sim 7 \times 10^{-3}$	100.0	Snoek due to O impurities	176
Nb–Ti	Nb–48% Ti (N atmosphere at 1200°C for 1 h)	340°C	0.6	$\sim 10^{-2}$	—	Snoek due to N	176
Nb–Ti	Nb–5at% Ti (plus D)	50 K	20×10^3				273
		100 K	20×10^3				
		170 K	20×10^3			Ti–D complexes reorientation	
Nb–V	Nb–0.3% V	~200 K	$2–2 \times 10^7$	2.5×10^{-3}	—	Dislocation damping	153
Nb–W–N	Nb–N (wires)	645 and 685 K	~1		143 and 153 respectively	Snoek	285
	Nb–2, 6 and 12at% W–N	645, 685 and 745 K	~1		143, 153 and 167 respectively		
Nb–Zr	Nb–1.0% Zr	~200 K	$2–2 \times 10^7$	1×10^{-3}	—	Dislocation damping	153
Nb–Zr	Nb–1% Zr–O+traces of N	~500°C	5×10^6	—	110.9	Snoek due to O in Nb	177
		~500°C	5×10^6	—	111.3	Substitutional–interstitial process involving O	177
		~500°C	5×10^6	—	123.4	Substitutional–interstitial process involving O pairs	177

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Nb–Zr	—	~500 °C	5×10^4	—	146.4	Snoek due to N in Nb	177
		~500 °C	5×10^4	—	147.3	Substitutional–interstitial process involving N	177
Ni	Zone refined (CW*)	138 K	3×10^4	2×10^{-3}–35×10^{-3}	—	Niblett and Wilks type	178
		248 K	3×10^4	1×10^{-2}–0.10	—	Bordoni type	178
Ni	Zone refined single crystal (CW*)	145–123 K	$\sim 2 \times 10^4$	Up to 1.6×10^{-3}	—	Associated with dislocation reactions	179
		223–263 K	$\sim 2 \times 10^4$	Up to 3.0×10	—	Bordoni type	179
Ni	99.99% Ni (CW* at RT)	155 K	10^3	—	29.7	Point defect/dislocation interaction	4
		350 K	10^3	—	51.0	Point defect/dislocation interaction	4
		397 K	10^3	—	69.4	Point defect/dislocation interaction	4
Ni	99.9% Ni	70 °C	0.7	—	77.0	Stress induced re-orientation of interstitial Ni atom pairs	180, 181
Ni	99.9999% Ni	150 °C	1	~0.1	—	Magneto-mechanical damping	182
Ni	99.99% Ni. (Area reduced 90%, annealed at 905 °C for 1 h)	432 °C	1.41	3.4×10^{-2}	308	Grain boundary	5
Ni	99.98% Ni	440–460 °C	0.5	0.10	—	Grain boundary	183
		630–720 °C	0.5	0.12	—	Stress relaxation at polygonized boundaries	183
Ni–Al–C	Ni–2% Al–0.5% C (Quenched)	280 °C	0.5	—	—	Diffusion of C in Ni–Al	184
Ni–B	Ni (pure)	470 °C; 670 °C	~1			All grain boundary	300
	Ni–0.0035wt% B	550 °C	~1				
Ni–C	(quenched)	230 °C	0.5		—	Diffusion of C in Ni	184
Ni–C	(cold-worked)	~430 °C	~1			Dislocation–C	276
Ni–Cr	0.5% Cr	530–800 °C	2	Depends on grain size	—	Grain boundary	185
Ni–Cr	Ni–33.3at% Cr	390 °C; 570 °C	0.7–1.5			Long range order	282
Ni–Cr	Ni–20wt% Cr	~700 °C	~1		370	Grain boundary	257
Ni–Cr–Ce	Ni–20wt% Cr–180 at ppm Ce	~700 °C	~1		200	Grain boundary	257
Ni–Cr–C	Ni–20% Cr–1.87% C (Quenched)	250 °C	0.9	—	98.3	Diffusion of C in Ni–Cr	186
Ni–Cu	Ni–20% Cu	~140 °C	1	$\sim 10^{-2}$	—	Magneto-mechanical damping	182
		(Varies)	1	$\sim 10^{-2}$	—	Magnetic ordering	182
Ni–Zr	0.1% Zr–0.5% Zr	~200 °C	~1	2×10^{-3}–8×10^{-4}	—	Magneto-mechanical damping	187
		~450 °C	~1	1×10^{-3}–3×10^{-4}	—	Grain boundary	187
		600–700 °C	~1	$< 1 \times 10^{-4}$–2×10^{-4}	—	'Blocking' peak	187
Pd–Cu–Si	Amorphous Pd–6at% Cu–16.5at% Si (1 mm wire)	147 °C			275 eV	Atomic diffusion	262
Pd–H	99.999% Pd (Annealed, electrolytically loaded with H) 40 At. % H–75 At. % H	70–80 K	2.7	$\sim 10^{-3}$	12.34–16.19	Stress induced ordering of H pairs in β phase	188

* Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Pd–H	PdH (β phase)	120 K	$\sim 10^3$	$\sim 2 \times 10^{-3}$	—	Snoek type due to H	189
	(Strained)	~150 K	$\sim 10^3$	$\sim 5 \times 10^{-3}$	—	Pinning of dislocations by interstitial impurities	189
Pd–D	99.999% Pd (Annealed, electrolytically loaded with D) 40 At. % D–73 At. % D	78–86 K	2.7	—	15.94–20.71	Stress induced ordering of D pairs in β phase	188
Pd–Si	80at% Pd–20at% Si with 1–2at% H (rapidly solidified amorphous)	180 K	100		0.31 eV	Short range diffusion of H	293
Pt	(Deformed 2.9%, annealed at 1 080 K for 1 h)	~70 K	5×10^3–6.5×10^4	5×10^{-6}	11.6	Associated with dislocations grouped into sub-grain boundaries	190
Pt	99.999% Pt (CW* 16% at 4.2 K)	125 K	0.8	8×10^{-3}	28.0	Bordoni type	1, 2
Pt	'Pure'	940–1 090 K	10^{-2}–1	—	275	Recrystallisation peak	191
Pu–Al	Pu–5 At. % Al	~65 K	10^7	—	—	Co-operative electron transition	192
Pu–Ce	Pu–6 At. % Ce	~65 K	10^7	—	—	Co-operative electron transition	192
Re	—	1 400 K	1.1	4×10^{-2}	586	Grain boundary	193
Se	(amorphous)	30 K	160×10^6			Attenuation of ultrasonic shear waves	302
Si	Surface damaged [100] by polishing	160 K	$\sim 2 \times 10^{-5}$	$\sim 2 \times 10^{-5}$	29	Associated with dislocations	132
	[111]	200 K	$\sim 2 \times 10^3$	$\sim 4 \times 10^{-5}$	29	Associated with dislocations	132
Si	Pure n-type [111] (Quenched from 1 000°C to 77 K)	689 K	1.2×10^3	$\sim 2 \times 10^{-4}$	130	Migration of O–vacancy complex	194
Si	Single crystal	655°C	10^5	1.4×10^{-5}	134.7	Electronic relaxation	195, 196
Si	Si whiskers (annealed) (thermally cycled)	~900 K ~1 300 K (max.) widened	~1 ~1			Relaxation in surface layers due to dislocation formation	277
Si–Cu	Si (Cu doped)	398 K	1.2×10^3	$\sim 3 \times 10^{-5}$	68	Migration of interstitial Cu	194
		626 K	1.2×10^3	$\sim 2 \times 10^{-4}$	96	Precipitation of Cu	194
Si–Li–B	Si–Li–0.01% B	210°C	1.74×10^4	6.5×10^{-5}	80.0	Reorientation of Li^+B^- pairs	197
Si–O	Single crystal	1 030°C	10^5	6×10^{-4}	246.0	Stress-induced diffusion of interstitial oxygen	195, 196
Sn	99.99% Sn	80°C	3×10^2	3×10^{-2}	79.5	Grain boundary	198
Ta	99.99% Ta (CW* 7%)	24.6 K	2.26×10^4	3.1×10^{-4}	3.7	Bordoni type	199
Ta	Zone refined (CW* 12% at RT)	124 K (α peaks)	0.8	9×10^{-4}	24.3	Bordoni type	151
		202 K (β peaks)	0.8	1.3×10^{-3}	41.4	Bordoni type	151
Ta	(Single crystal <111> orientation) CW* 3.1%	170 K	17	19×10^{-3}	—	Snoek–Köster type	239
Ta	(Single crystal)	150 K	0.7	—	4×10^{-3}	Dislocation kink formation	240
Ta	—	1 100°C	0.65	7×10^{-2}	418	Grain boundary	193
Ta	99.89% (Annealed at 1 700°C)	1230°C	1.0	5.6×10^{-2}	406	Grain boundary	142

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Ta–C	Ta–0.1% C	338 °C	0.55	2.6×10^{-2}	161.1	Snoek type	200, 171
Ta–H	99.9% Ta (CW* 1.7% H charged)	27 K	2×10^{4}–10^{5}	$\sim 5 \times 10^{-5}$	1.6	Associated with dislocations	162
Ta–H	—	100 K	1.75×10^{2}	2.4×10^{-3}–2.7×10^{-3}	—	Bordoni type (?)	201, 162
		190 K	1.75×10^{2}	—	34.7	Stress induced ordering in the Ta_2H phase	201, 162
Ta–H	8.5 At. % H–42.4 At. % H	1 °C	1.75×10^{2}	6×10^{-3}–1.6×10^{-2}	52.3	Stress induced ordering in Ta_2H phase	201
		36 °C	1.75×10^{2}	3×10^{-3}–1.9×10^{-2}	—	Long range ordering of H in Ta_2H phase	201
		54 °C	1.75×10^{2}	2.6×10^{-3}–8.5×10^{-3}	—	Short range ordering of H in Ta_2H phase	201
Ta–N	Ta–0.11% N	334 °C	0.6	9×10^{-2}	156.9	Diffusion of interstitial N	202
		362 °C	0.6	9×10^{-2}	167.4	Diffusion of interstitial N atom pairs	202
Ta–O	Ta–0.081% O	137 °C	0.6	8×10^{-2}	104.6	Diffusion of interstitial O	203, 204
		162 °C	0.6	8×10^{-2}	104.6	Diffusion of interstitial O atom pairs	203, 204
Ta–O	Ta–0.01% O (CW* 30%)	340 °C	0.5	4.4×10^{-3}	151	Köster type	205
Ta–Re–N	Ta–(1.3 At. % Re–3.8 At. % Re)–600 ppm N	~340 °C	0.8	$\sim 6 \times 10^{-3}$	156.9	Snoek type due to N	206
		~380 °C	0.8	$\sim 10^{-3}$	168.2	Snoek type due to N	
Te	—	~400 K	1.44×10^{4}	$\sim 10^{-4}$	—	Recombination of election–hole pairs	207
Ti	99.7% Ti (CW* at RT)	220 K	10^{3}	—	33.9	Bordoni type (?)	4
		305 K	10^{3}	—	42.3	Point defect/dislocation interaction	4
		336 K	10^{3}	—	51.9	Point defect/dislocation interaction	4
Ti	High purity (cold worked)	133 K; 173 K	1			Bordoni	309
		198 K; 223 K	1			Hasiguti	
Ti	99.6% Ti	775 °C	1.0	0.38	201	Grain boundary	208
Ti–Al	0.04% Al–0.12% Al	675–725 °C	1.0	2.5×10^{-2}–0.4	218–293	Grain boundary	208
Ti–Al–V	Ti–6wt% Al–4wt% V (alpha/beta quenched)	~ −83 to −113 °C	1			Hydride precipitation	261
		~ −53 to 7 °C	1			Dislocation/hydrogen	
Ti–Al–V	Ti–6wt% Al–4wt% V (commercially heat-treated)	116 K	2×10^{3}		5.6 kcal mol^{-1}	Snoek H peak in beta phase	292
		289 K	2×10^{3}		11.1 kcal mol^{-1}	Snoek H peak in alpha phase	
Ti–Au	Ti–0.05% Au	715 °C	1.0	4×10^{-2}	259.4	Grain boundary	208
Ti–Cr	Ti–10 At. % Cr (Quenched from 1 000 °C)	152 K	$\sim 10^{5}$	1.75×10^{-2}	29	Associated with vacancies in 2 co-existing electronic environments	209
Ti–H	Ti–0.15% H	273 K	1.2	1.6×10^{-2}	62.8	Diffusion of interstitial H	210
Ti	Ti–5wt% Mo–5wt% V–8wt% Cr–3wt% Al	130 °C			0.29 eV	H in beta phase	253
		45 °C			0.49 eV	Alpha phase	

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Ti–Mo–Zr–Sn	Ti–11.5wt% Mo–6wt% Zr–4.5wt% Sn (Beta III) (beta solid solution)	−170°C; 250°C	~1			Beta/omega shear trans; ditto diffusion	284
Ti–Nb	Ti–25 At. % Nb (Quenched from 1000°C)	177 K	$\sim 10^5$	6.15×10^{-3}	29	Associated with vacancies in 2 co-existing electronic environments	209
Ti–Nb	0.04% Nb–0.12% Nb	625–675°C	1.0	2.7×10^{-2}–3.7×10^{-2}	213–264	Grain boundary	208
Ti–Ni	Ti–10 At. % Ni (Quenched from 1000°C)	152 K	$\sim 10^5$	2.15×10^{-3}	29	Associated with vacancies in 2 co-existing electronic environments	209
Ti–Ni	TiNi Intermetallic compound. (Ni–49% Ti).	203 K	~1	$\sim 10^{-2}$	36.6	Dislocation motion (?)	211
	Annealed at 800°C	223–313 K	~1	$\sim 10^{-2}$	—	Fine structure of 203 K peak	211
Ti–Ni	—	350°C	~1	$\sim 10^{-3}$	—	Impurity effect (?)	211
		600°C	~1	$\sim 2 \times 10^{-2}$	—	Transition from TiNi (II) to TiNi (I)	211
Ti–O	Ti–2 At. % O	450°C	1.0	1.2×10^{-2}	200.8	Diffusion of interstitial O in presence of impurities	212, 213,
Ti–O	Ti–0.6 At. % O	660–650°C	1.0	2.5×10^{-2}	188.3	Grain boundary	214
Ti–V	Ti–20 At. % V (Quenched from 1000°C)	140 K	$\sim 10^5$	2.2×10^{-3}	29	Associated with vacancies in 2 co-existing electronic environments	209
Ti–V	Ti–50 At. % V (Quenched from 1000°C)	161 K	$\sim 10^5$	2×10^{-3}	29	Associated with vacancies in 2 co-existing electronic environments	209
Ti–V	0.02% V–0.12% V	600–700°C	1.0	3×10^{-2}–0.42	230–335	Grain boundary	208
Ti–V–H	25at% V	84 K/123 K	2/1.5		16	Snoek type	254
Ti–Zr	0.02% Zr–0.12% Zr	650–700°C	1.0	3.1×10^{-2}–3.6×10^{-2}	251–502	Grain boundary	208
U	99.9% U (CW* at RT)	155 K	10^3	—	23.0	Bordoni type (?)	4
		202 K	10^3	—	42.3	Point defect/dislocation interaction	4
V–C	—	162°C	0.55	6.4×10^{-3}	114.2	Diffusion of interstitial C	215
V–H	99.99% V + 600 ppm H	170 K	500	13×10^{-4}	—	Point defect/dislocation interaction	243
V–H	—	18.5 K	2×10^2–10^5	$\sim 6 \times 10^{-5}$	1.1	Dislocation damping	216
		250 K	~	$\sim 10^{-5}$	—	Point defect/dislocation interaction	216
		285 K	~	$\sim 10^{-5}$	—	Point defect/dislocation interaction	216
V–H	99.99% + H in soln	203 K	2×10^2–10^5	$\sim 7 \times 10^{-4}$	50	Stress induced ordering in β phase	216
V–H	1.2 At. % H–14.5 At. % H	195 K	75	8×10^{-3}–7.2×10^{-2}	37.87	Diffusion of interstitial H	217
V–N	—	272°C	1.0	2.2×10^{-2}	142.7	Diffusion of interstitial N	218
V–O	—	174°C	0.55	1.2×10^{-2}	122.6	Diffusion of interstitial O	215

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
W	99.999 8% W	—		—	469	Grain boundary	219
		—		—	46	Movement of vacancies	219
		150 K		—	33	Movement of divacancies	219
W	High purity (CW* 3% at 400°C)	165 K	1.5×10^4	10^{-3}	24.3	Bordoni type	151, 200
W	99.99% W single crystal	~300°C	~1	$\sim 2 \times 10^{-4}$	146	Snoek type of uncertain origin	221
		~400°C	~1	$\sim 2 \times 10^{-4}$	188	Snoek type associated with C impurities	221
W	Commercial purity	1250°C	0.94	0.28	481–523	Grain boundary	193, 222
W	(CW* at RT)	1535°C	~70	~0.2	—	Primary recrystallization peak	223
W	Zone refined	1600–1650 K	10^{-2}–0.25	~0.6	477	Recrystallization peak	224
W	Commercial purity	1900°C	0.35	0.56	619	Grain boundary	222, 225
W	(CW* at RT, annealed at 3000°C)	~2000°C	~70	~0.1	—	Grain boundary	223
W–Re	W–20% Re	1950°C	1.08	$\sim 5 \times 10^{-2}$	510	Grain boundary	223
Zn	99.999% Zn (Compressed 2.4% at RT)	~100 K	$\sim 2 \times 10^7$	—	5.8	Dislocation movements in basal plane	226
		~170 K	$\sim 2 \times 10^7$	—	15.4	Dislocation movements in prismatic plane	226
		~230 K	$\sim 2 \times 10^7$	—	19.2	Dislocation movements in pyramidal plane	226
Zn	99.999wt% Zn (worked single crystals)	140–220 K	1×10^3			Bordoni	271
Zn	99.999% Zn (Annealed at 100°C for 12 h)	383 K	~1	~0.3	95	Grain boundary	227
Zn–Al	22wt% Al (2 h at 360°C, w.q.)	~25°C	1–3	9×10^{-2}			255
	22wt% Al–0.3wt% Cu (2 h at 360°C, w.q.)	~25°C	1–3	3×10^{-2}			
	As above + 0.021wt% Mg (2 h at 360°C, w.q.)	~25°C	1–3	1.44×10^{-2}			
Zr	99.999% Zr	80 K	1.5×10^5	$\sim 5 \times 10^{-4}$	28	Bordoni type	228
	(7 k bar pressure)	250 K	1.5×10^5	$\sim 2 \times 10^{-3}$	13	(?)	228
Zr (–O)	High purity (deformed and annealed alpha Zr)	480°C; 530°C; 600°C	4			Dislocation/O interaction; longitudinal and transverse motion in dislocation core	295
Zr	99.9% Zr (CW* at RT)	200–220 K	10^3	9×10^{-4}	33.9(?)	Bordoni type(?)	41, 229
		305 K	10^3	—	42.3	Point defect/dislocation interaction	4
Zr	—	336 K	10^3	—	51.0	Point defect/dislocation interaction	4
Zr	99.9% Zr	600°C	1.0	4.6×10^{-2}	218–243	Grain boundary	230, 231
		860°C	1.0	0.28	—	α–β transformation	230, 232
Zr–Cu	Zr–up to 2.5% Cu (Annealed at 900°C for 1 h, CW* 10%)	~220 K	1.3×10^4	Up to 1.5×10^{-3}	33.8	Bordoni type	233

*Cold worked.

Table 15.8 ANELASTIC DAMPING—*continued*

Alloy	*Composition and physical condition*	*Peak temp.*	*Frequency* Hz	*Modulus defect*	*Activation energy* kJ mol^{-1}	*Mechanism or type*	*Ref.*
Zr–Cu–Mo	Zr–0.5% Cu–0.5% Mo (Deformed 10%)	~230 K	1.3×10^4	2×10^{-3}	33.8	Bordoni type	233
Zr–H	Zr–0.89% H	228 K	1.0	4×10^{-3}	48.5	Diffusion of interstitial H	231
Zr–H	Zr–1.28% H	5°C	1.0	2.4×10^{-2}	71.1	Diffusion of interstitial H atom pairs	231
Zr–H	Zr–1.15% H	~50°C	$\sim 2 \times 10^4$	$\sim 1 \times 10^{-3}$	—	Associated with δ and γ phases	234
		~130°C	$\sim 2 \times 10^4$	$\sim 1 \times 10^{-2}$	—	Associated with δ and γ phases	234
Zr–H	Zr–0.26% H	230°C	1.0	5×10^{-3}	—	Associated with ZrH precipitate	231
Zr–Hf–O	Zr–(0.005% Hf–1% Hf)–O	530°C 540°C	~1	$\sim 7 \times 10^{-3}$ $\sim 10^{-2}$	—	Grain boundary	235
		422°C	~1	2×10^{-4}–4×10^{-4}	201	Diffusion of O in lattice	235
Zr–Mo	Zr–6 At.% Mo (Quenched from 1000°C)	213 K	$\sim 10^5$	1.36×10^{-2}	29	Associated with vacancies in 2 co-existing electronic environments	209
Zr–Nb	Zr–5% Nb	12 K	10^5	$\sim 2 \times 10^{-4}$	1.9	?	236
Zr–Nb	5% Nb–25% Nb (CW*)	40 K		$\sim 6 \times 10^{-4}$	4.8	Jahn–Teller type	236
		160 K	10^5	Depends on CW	29	Stress induced re-orientation of atoms	236
Zr–Nb	12 At.% Nb–75 At.% Nb (Quenched from 1000°C)	163–207 K	$\sim 10^5$	1.5×10^{-4}–5.9×10^{-3}	29	Associated with vacancies in 2 co-existing electronic environments	209
Zr–O	Zr–1.95% O	420°C	~1	Depends on O $conc^n$	201	Diffusion of O in lattice	235
Zr–V	Zr–10 At.% V (Quenched from 1000°C	193 K	$\sim 10^5$	1.5×10^{-4}	29	Associated with vacancies in 2 co-existing electronic environments	209

*Cold worked.

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15.3 Shape memory alloys

15.3.1 Mechanical properties of shape memory alloys

Most shape memory alloys have compositions at which the crystallographic structure can change reversibly and reproducibly from a higher temperature phase to one of lower symmetry by a small change in temperature or by a change in mechanical stress at temperatures just above the transformation temperature at zero stress.

In most shape memory alloys (and in all the industrially useful alloys), the change of structure usually occurs over a narrow range of temperature by means of a self-accommodating martensitic transformation, during which a small amount of heat is evolved or absorbed depending on the direction of the temperature change. This usually gives rise to a thermal hysteresis of about 10 to 40°C over which the parent phase (usually referred to as 'austenite') and the martensite can co-exist.

If a stressed shape memory alloy is thermally cycled through its martensitic transformation temperature, the strain–temperature relationship will take the form of a closed hysteresis loop similar in shape to the *B–H* curve of ferromagnetic alloys. If a shape memory alloy is cooled to below its M_f temperature, it undergoes little change in shape or volume. If it is then deformed

plastically to a new shape, it will recover its original undeformed shape on re-heating to a temperature above its A_s temperature. The amount of strain which can be recovered in this way is not unlimited but depends on the nature of the alloy. For example, the maximum recoverable strain is about 8% in Ti–Ni alloys and 10–12% in Cu–Zn alloys (although the latter cannot be achieved in industrially useful alloys).

On cooling through the transformation to the martensitic state, the temperatures at which the transformation starts and finishes at zero applied stress are denoted by M_s and M_f respectively. On re-heating, the temperatures at which the reverse transformation to the high temperature takes place are A_s and A_f respectively. These temperatures can be determined experimentally by thermal or dilatometric analysis or by changes in electrical resistivity. The M_s temperature is raised progressively by applied stress; the M_d temperature is the highest temperature at which the transformation can be induced by stress. Figure 15.1 illustrates these points.[11] If an alloy is deformed above the M_s but below the M_d temperature, a stress-induced martensitic strain can be obtained. This is completely recovered on unloading (*see* Figures 15.4 and 15.7).

Shape memory does not always appear to depend on the martensitic transformation. Small amounts of shape memory can be obtained in primary solid solutions of alloys of low stacking fault energy.[16] Examples are shown in Table 15.9, e.g. Cu–Al and Cu–Si primary solid solutions and some stainless steels. Although the latter undergo martensitic transformations to the alpha prime martensite, this is too brittle to deform. Shape memory is only found when the stainless steel is deformed at very low temperatures but above the M_s to form both delta and some alpha martensite. 20% deformation may be needed to obtain 1.0–1.5% shape memory strain and it has proved to be of little industrial relevance so far.

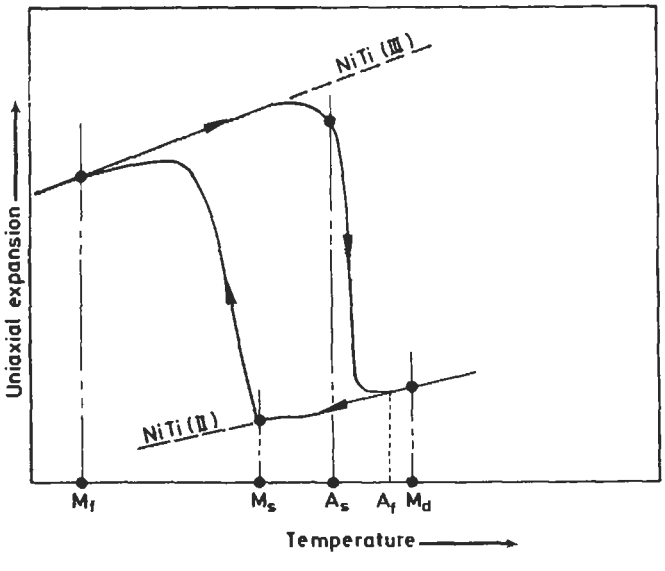


Figure 15.1 *Typical uniaxial dimensional change behaviour for drawn wire.* Ti–55.0% Ni–0.07%C. *After W. B. Cross* et al.[11]

Though most work has concentrated on Ti–Ni and related alloys because of their industrial importance, the shape memory phenomenon has been demonstrated in a wide range of alloys, some of which are listed in Table 15.9.

M_s temperatures can be varied continuously by changing the composition. Examples include: (i) changing Ni content in Ti–Ni alloys; (ii) partially replacing Ni by Fe, Co or Pd in Ti–Ni alloys; and (iii) changing Al and Zn contents in Cu–Al–Zn alloys or by partially replacing either element by others such as Sn, Mn, etc. Such variations also change the character of the alloys. Table 15.9 shows typical compositions for which data are published but it is possible to derive additional alloys within the ternary and more complex systems.

Note that if shape memory alloys are cooled under stress, the M_s temperature is raised in direct proportion to stress below M_o (*see* Figure 15.7).

Note also that the M_s, etc temperatures are not exact in that for a given composition they can be changed by heat-treatment and by cold-working. Figure 15.8 illustrates an example of the extent to which the hysteresis can be widened in a Cu-based alloy.[37]

Table 15.9 COMPOSITIONS AND TRANSFORMATION TEMPERATURES OF SHAPE MEMORY ALLOYS

Alloy composition wt%[(1)]	*M_s temperature at zero stress at* °C	*A_s temperature at zero stress* °C	*Maximum shape memory strain* %	*Reference*
Au–28at% Cu–46 At.% Zn	−15			6
Au–47.5% Cd	60	70		13
Au–12.9% Cu–25.5% Zn	−100		1.55	32
Au–15.2% Cu–28.0% Zn	−50		~1.0; brittle g.b. phase	32
Au–16.0% Cu–32.3% Zn	−118		ditto; Zn too high	32
Au–22.3% Cu–31.4% Zn	−64		2.15	32
Au–28.7% Cu–31.1% Zn	< −196		?; Zn too low	32
Cu–2.50% Al–31.75% Zn	−105		10.25	15
Cu–3.94% Al–25.60% Zn	54	48	>2.0	23
Cu–4.00% Al–26.10% Zn	24	23	14% (5–6% reversible)	20
Cu–6.00% Al–22.00% Zn	−50		4.8	15
Cu–7.50% Al–17.00% Zn	−10		4	15
Cu–11.75% Al–6.00% Zn	50		2.8	15
Cu–10.50% Al–7.25% Zn	140		3.9	15
Cu–11.25% Al–4.75% Zn	170		2	15
Cu–11.75% Al–2.50% Zn	250		1.9	15
Cu–4.90% Sn–31.25% Zn	−70		1	15
Cu–1.75% Si–34.50% Zn	−140		6.3	15
Cu–2.25% Si–31.25% Zn	−50		6	15
Cu–3.25% Si–27.50% Zn	75		2.95	15
Cu–12.00% Al–2.00% Mn	240		0.95	15
Cu–11.25% Al–4.25% Mn	160		0.45	15
Cu–10.75% Al–6.00% Mn	100		0.45	15
Cu–10.40% Al–7.00% Mn	83			21
Cu–10.60% Al–7.00% Mn	52			21
Cu–11.00% Al–7.00% Mn	5			21
Cu–11.10% Al–7.00% Mn	−10			21
Cu–12.50% Al–1.00% Fe	300		1.75	15
Cu–12.50% Al–8.00% Fe	250		1.1	15
Cu–13.25% Al–2.75% Ni	82		2.9	15
Cu–8.0% Al	N.A.	N.A.	1.05	16
Cu–4.0% Si	N.A.	N.A.	1.4	16
Cu–14.2% Al–4.3% Ni	−20	−15		8
Cu–40% Zn	−70	−120		8
Cu–34.7% Zn–3.0% Sn	−52	−50	4.5 (polycrystal) 8.5 (single crystal)	9
Fe–15% Cr–15% Ni–15% Co	< −196	−196 to 40	1.45	16
Fe–20% Cr–10% Ni–1% Al	< −196	−196 to 40	0.45	16
Fe–20% Mn–3.75% Ti	< −196	−196 to 40	1.4	16

Table 15.9 COMPOSITIONS AND TRANSFORMATION TEMPERATURES OF SHAPE MEMORY ALLOYS—*continued*

Alloy composition wt%[1]	M_s *temperature at zero stress at* °C	A_s *temperature at zero stress* °C	*Maximum shape memory strain* %	*Reference*
Fe–20% Cr–15% Ni	< −196	−196 to 40	1.05	16
Fe–17% Cr–19% Ni	> −196	−196 to 40	0.9	16
Fe–30% Mn–6.5% Si	<20	20 to 400	2.1	22
Fe–24% Mn–3% Si	123	188	1.5–1.75	24
Fe–26% Mn–4% Si	106	182	1.5–1.75	24
Fe–27% Mn–3% Si	103	176	1.5–1.75	24
Fe–28% Mn–3% Si	102	164	1.5–1.75	24
Fe–28% Mn–4% Si	62	162	1.5–1.75	24
Fe–29% Mn–4% Si	88	164	1.5–1.75	24
Fe–32% Mn–4% Si	27	134	1.5–1.75	24
Fe–33% Mn–4% Si	22	131	1.5–1.75	24
Fe–34% Mn–4% Si	8	127	1.5–1.75	24
Fe–35% Mn–4% Si	−10	123	1.5–1.75	24
Ti–50.2at% Ni	35	50	1.4 (reversible)	17
Ti–50.2at% Ni	10	57		18
Ti–50.2at% Ni	~25	~55	5.5% (~4% reversible)	19
Ti–56.4% Ni	5			26
Ti–55.5% Ni	10			26
Ti–55.0% Ni	35			26
Ti–53.7% Ni	75			26
Ti–54.8% Ni	62			27
Ti–52–56% Ni	~RT			1
Ti–53.5% Ni	98			2
Ti–54.0% Ni	140			2
Ti–54.5% Ni	170	175	8.0	2,4
Ti–55.0% Ni	140			2
Ti–55.5% Ni	30			2
Ti–56.0% Ni	−25			2
Ti–56.5% Ni	−50			2
Ti–51at% Ni	28	62		7
TiNi[2]	166			3
TiCo	−238			3
$TiNi_xCo_{1-x}$[3]	166 where $x=1$ −238 where $x=0$			3
TiFe	~ −269			3
Ti–35% Nb	−175	184	~2.5	10
Ti–51.4% Ni–3.57% Co				
0.3 in. rod	−51	−40	6 to 10	11
0.003 in. foil	−65	−45	6 to 10	11
0.01 in. wire	−73	−51	6 to 10	11
Ti–55.0% Ni–0.07% C				
0.2 in. rod	21	60	6 to 10	11
0.003 in. foil	27	43	6 to 10	11
0.01 in. wire	18	43	6 to 10	11
Ti–54.6% Ni–0.06% C				
0.625 in. rod	43	71	6 to 10	11
0.003 in. foil	38	66	6 to 10	11
0.01 in. wire	32	54	6 to 10	11
Ti–47.0% Ni–7% Cu	63			27
Ti–44.5% Ni–10% Cu	52			27
Ti–32.0% Ni–22% Cu	74			27
Ti–27.0% Ni–29% Cu	20			27
Ti–47.0at% Ni–3at% Fe	−180	−88		30
Ti–52.85% Ni–0.28% Fe	34	35	8 (0.094 rad in torsion)	14, 33, 34
Ti–47.0at% Ni–9at% Nb	−90	−56 up to 55		30
Ti–50at% Pd	533	573	~2.0	28, 29
Ti–50at% Pd	510	520		36

Table 15.9 COMPOSITIONS AND TRANSFORMATION TEMPERATURES OF SHAPE MEMORY ALLOYS—*continued*

Alloy composition wt%[1]	M_s *temperature at zero stress at* °C	A_s *temperature at zero stress* °C	*Maximum shape memory strain* %	*Reference*
Ti–50at% Pd	563	580	2.39	35
Ti–40.0at% Pd–10.0at% Ni	403	419	2.66	35
Ti–30.0at% Pd–20.0at% Ni	241	230	4.38	35
Ti–20.0at% Pd–30.0at% Ni	95	90	1.84	35
Ti–10.0at% Pd–40.0at% Ni	−18	−26		35
Ti–50.0at% Ni	55	80		35
Ti–5.0at% Pt–45.0at% Ni	29	36		35
Ti–10.0at% Pt–40.0at% Ni	18	−27		35
Ti–20.0at% Pt–30.0at% Ni	300	263	2.17	35
Ti–30.0at% Pt–20.0at% Ni	619	626		35
Ti–50.0at% Pt	1070	1040		36
Ti–44at% Pd–6at% Fe	321	335	5.0	28, 29
Ti–42at% Pd–8at% Fe	293	250		28
Ti–40at% Pd–10at% Fe	173	178		28
Ti–38at% Pd–12at% Fe	96	99		28
Ti–36at% Pd–14at% Fe	25	25		28
Ti–34at% Pd–16at% Fe	−49	−45		28
Ti–42at% Pd–4at% Fe	228	216		28
Ti–40at% Pd–6at% Fe	119	124		28
Ti–38at% Pd–8at% Fe	18	3		28
ZrRu[4]	−233			3
ZrRh[4]	380			3
ZrPd[4]	727			3
U–4.0% Mo		200		31
U–4.5% Mo		80		31
U–5.0% Mo		50	3.2	31
U–6.0% Mo		−50		31
U–4.0% No		~250		31
U–5.0% Nb		~200		31
U–7.0% Nb		~100		31
U–14at% Nb	160	90	4.8	25
U–9at% Nb[5]	0	150		5
U–12at% Nb[5]	0	150		5
U–15at% Nb[5]	0	60		5
U–18at% Nb[5]	−196	0		5

[1] Unless otherwise stated. [2] *See also* Figure 15.2.[3] [3] *See* Figures 15.3.
[4] Non-linear interpolation between their compounds is possible. Relationship is of form $\log_e (M_s K) \propto x$ where x is in the range 0–1 in $Zr–Ru_x–Rh_{1-x}$ etc.
[5] M_s and A_s not accurately determined but are within these temperature ranges.

Table 15.10 PHYSICAL AND MECHANICAL PROPERTIES OF A TITANIUM–55% NICKEL SHAPE MEMORY ALLOY

Property	*Value*
Density	$6.45\,g\,cm^{-3}$
M.p.	1310°C
Magnetic permeability	<1.002
Electrical resistivity	80 μΩ cm at 20°C 132 μΩ cm at 900°C
Coefficient of thermal expansion (24–900°C)	$10.4 \times 10^{-6}\,°C^{-1}$
Mechanical properties at 20°C (i.e. below M_s)	
0.2% yield stress	207 MPa
UTS	861 MPa
Elongation %	22
Reduction in area %	20
Impact (unnotched)	159J at 20°C 95J at 80°C
Fatigue (rotating beam)	$>25 \times 10^6$ cycles at 483 MPa

Note

If recovery is prevented mechanicaly, the TiNi will exert a stress and is capable of doing work when heated to above the A_s temperature. Samples of Ti–55.0% Ni–0.07%*C* were capable of exerting a stress of up to 758 MPa at 171°C (*see* Figure 15.5). The amount of mechanical work which this alloy was capable of doing was 17–20 J cm^{-3} on heating from 24°C to 171°C.

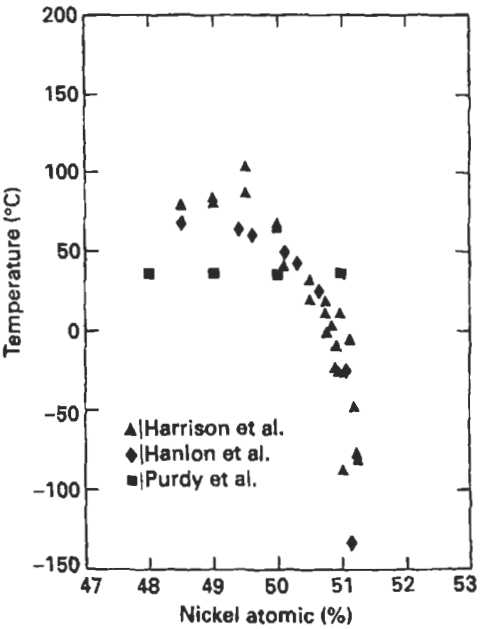


Figure 15.2 *The dependence of the transformation temperature M_s on composition of Ti–Ni alloys, after K. N. Melton*[39]

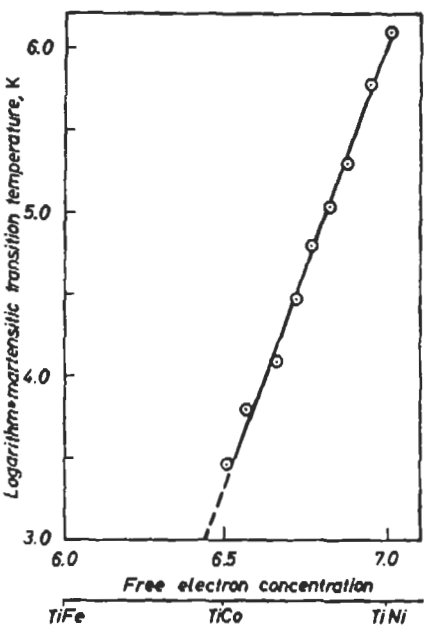


Figure 15.3 *See Table 15.9 after F. E. Wang and W. J. Buehler*[3] •Natural logarithm

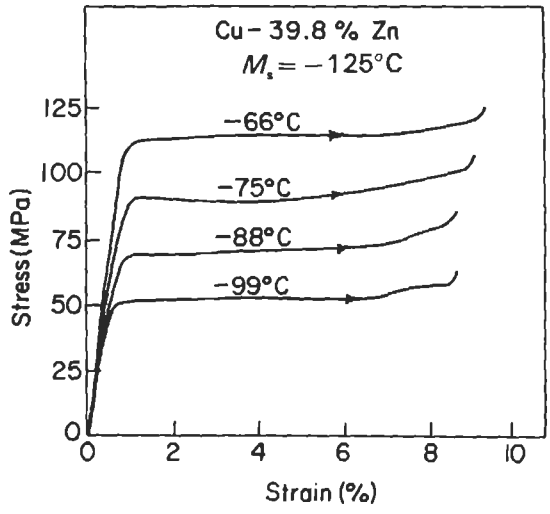


Figure 15.4 *Stress–strain curves for a Cu–Zn single crystal loaded in tension above M_s. As the M_s temperature is approached, the stress required to induce martensite is lowered, after C. M. Wayman and T. W. Duerig*[38]

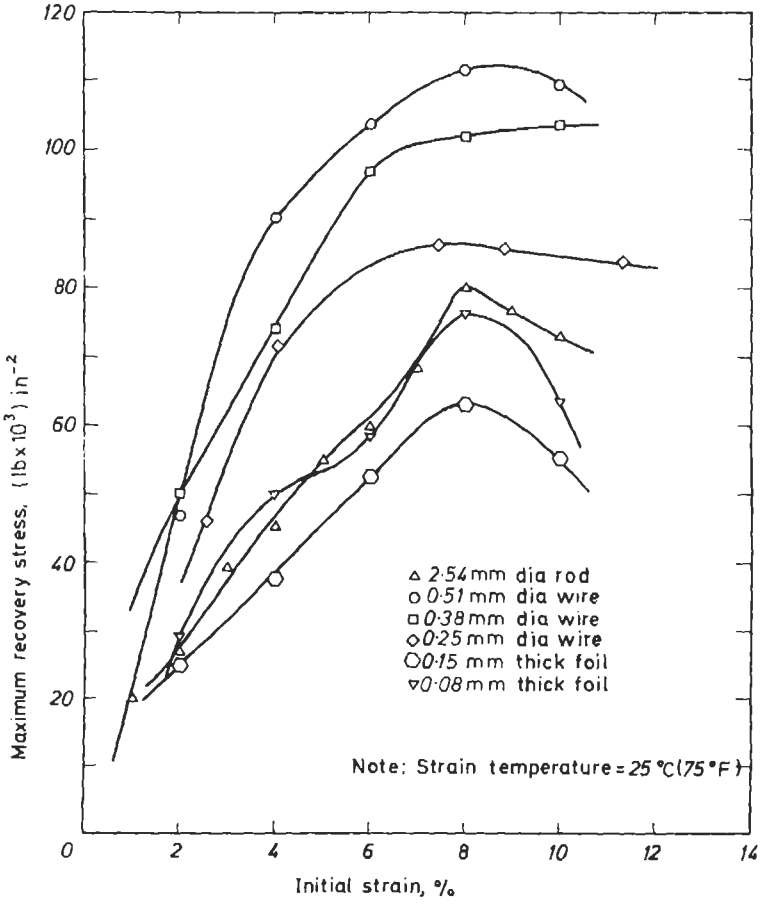


Figure 15.5 *Maximum recovery stress versus initial strain curves for* Ti–55.0% Ni–0.0% *C. See Table 15.9, after W. B. Cross* et al.[11]

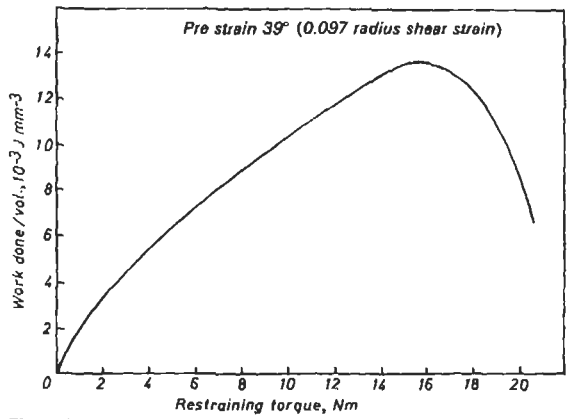


Figure 15.6 *The relationship between the capacity of* TiNi *alloy to do work in torsion and the restraining torque.*[14]

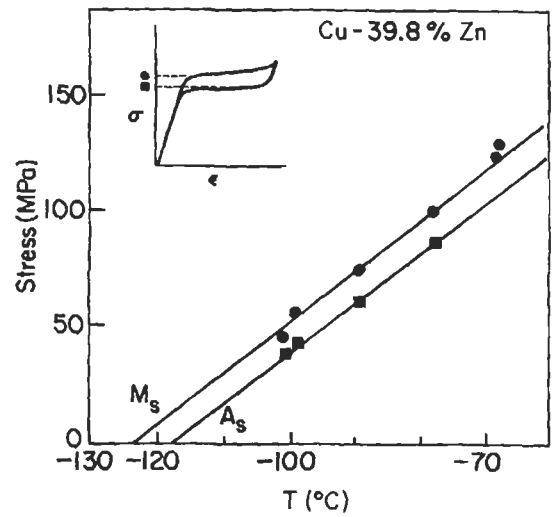


Figure 15.7 *Plotting the plateau stresses such as shown in Figure 15.4 as a function of temperature gives a linear plot which obeys the Clausius–Clapeyron relationship. The alloy's zero stress A_s and M_s are marked on the ordinate.*[38]

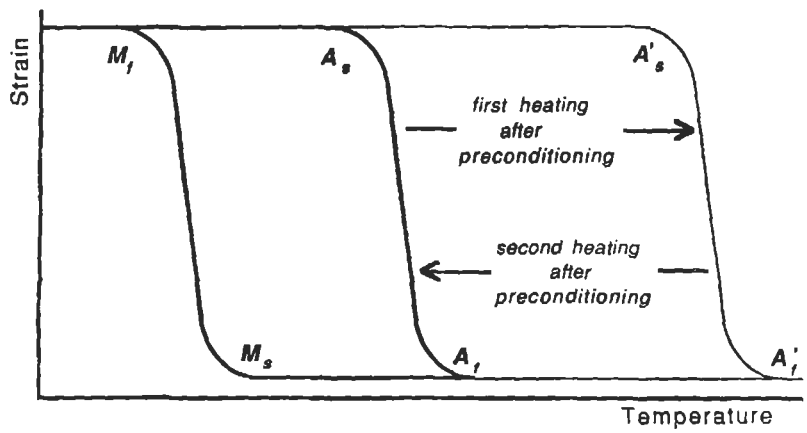


Figure 15.8 *The preconditioning process is a one-time displacement of A_s and A_f. Once recovery is complete, martensite can be reformed, after which A_s and A_f are restored to their original values, after Duerig* et al.[37]

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16 Temperature measurement and thermoelectric properties

16.1 Temperature measurement

The unit of the fundamental physical quantity known as thermodynamic temperature, symbol T, is the kelvin, symbol K, defined as the fraction 1/273.16 of the thermodynamic temperature of the triple point of water†.

Because of the way earlier temperature scales were defined, it remains common practice to express a temperature in terms of its difference from 273.15 K, the ice point. A thermodynamic temperature, T, expressed in this way is known as a Celsius temperature, symbol t, defined by:

$$t/°C = T/K - 273.15$$

The unit of Celsius temperature is the degree Celsius, symbol °C, which is by definition equal in magnitude to the kelvin. A difference of temperature may be expressed in kelvins or degrees Celsius.

The International Temperature Scale of 1990 (ITS-90) defines both International Kelvin Temperatures, symbol T_{90}, and International Celsius Temperatures, symbol t_{90}. The relation between T_{90} and t_{90} is the same as that between T and t, i.e.:

$$t_{90}/°C = T_{90}/K - 273.15$$

The unit of the physical quantity T_{90} is the kelvin, symbol K, and the unit of the physical quantity t_{90} is the degree Celsius, symbol °C, as is the case for the thermodynamic temperature T and the Celsius temperature t.

The International Temperature Scale of 1990[1] was adopted by the International Committee of Weights and Measures at its meeting in 1989, in accordance with the request embodied in Resolution 7 of the 18th General Conference of Weights and Measures of 1987. This Scale supersedes the International Practical Temperature Scale of 1968 (amended edition of 1975) and the 1976 Provisional 0.5 K to 30 K Temperature Scale.

The ITS-90 extends upwards from 0.65 K to the highest temperature practicably measurable in terms of the Planck radiation law using monochromatic radiation. The ITS-90 comprises a number of ranges and subranges throughout each of which temperatures T_{90} are defined. Several of these ranges or subranges overlap, and where such overlapping occurs differing definitions of T_{90} exist: these differing definitions have equal status. For measurements of the very highest precision there may be detectable numerical differences between measurements made at the same temperature but in accordance with differing definitions. Similarly, even using one definition, at a temperature between defining fixed points two acceptable interpolating instruments (e.g. resistance thermometers) may give detectably differing numerical values of T_{90}. In virtually all cases these differences are of negligible practical importance and are at the minimum level consistent with a scale of no more than reasonable complexity: for further information on this point, see 'Supplementary Information for the ITS-90'[2].

The ITS-90 has been constructed in such a way that, throughout its range, for any given temperature the numerical value of T_{90} is a close approximation to the numerical value of T according to best estimates at the time the scale was adopted. By comparison with direct measurements of thermodynamic temperatures, measurements of T_{90} are more easily made, are more precise and are highly reproducible[3].

† 'Comptes Rendus des Séances de la Treizième Conférence Générale des Poids et Mesures (1967–1968)', Resolutions 3 and 4, p. 104.

There are significant numerical differences between the values of T_{90} and the corresponding values of T_{68} measured on the International Practical Temperature Scale of 1968 (IPTS-68), see Figure 16.1 and Table 16.1. Similarly there were differences between the IPTS-68 and the International Practical Temperature Scale of 1948 (IPTS-68), and between the International Temperature Scale of 1948 (ITS-48) and the International Temperature Scale of 1927 (ITS-27)[3].

Between 0.65 K and 5.0 K T_{90} is defined in terms of the vapour-pressure temperature relations of ^{3}He and ^{4}He.

Between 3.0 K and the triple point of neon (24.556 1 K) T_{90} is defined by means of a helium gas thermometer calibrated at three experimentally realizable temperatures having assigned numerical values (defining fixed points) and using specified interpolation procedures.

Between the triple point of equilibrium hydrogen (13.803 3 K) and the freezing point of silver (961.78°C) T_{90} is defined by means of platinum resistance thermometers calibrated at specified sets of defining fixed points and using specified interpolation procedures.

Table 16.1 THE DIFFERENCES BETWEEN ITS-90 AND EPT-76, AND BETWEEN ITS-90 AND IPTS-68

$(T_{90}-T_{76})$/mK

T_{90}/K	0	1	2	3	4	5	6	7	8	9
0						−0.1	−0.2	−0.3	−0.4	−0.5
10	−0.6	−0.7	−0.8	−1.0	−1.1	−1.3	−1.4	−1.6	−1.8	−2.0
20	−2.2	−2.5	−2.7	−3.0	−3.2	−3.5	−3.8	−4.1		

$(T_{90}-T_{68})$/K

T_{90}/K	0	1	2	3	4	5	6	7	8	9
10					−0.006	−0.003	−0.004	−0.006	−0.008	−0.009
20	−0.009	−0.008	−0.007	−0.007	−0.006	−0.005	−0.004	−0.004	−0.005	−0.006
30	−0.006	−0.007	−0.008	−0.008	−0.008	−0.007	−0.007	−0.007	−0.006	−0.006
40	−0.006	−0.006	−0.006	−0.006	−0.006	−0.007	−0.007	−0.007	−0.006	−0.006
50	−0.006	−0.005	−0.005	−0.004	−0.003	−0.002	−0.001	0.000	0.001	0.002
60	0.003	0.003	0.004	−0.004	0.005	0.005	0.006	0.006	0.007	0.007
70	0.007	0.007	0.007	−0.007	0.007	0.008	0.008	0.008	0.008	0.008
80	0.008	0.008	0.008	−0.008	0.008	0.008	0.008	0.008	0.008	0.008
90	0.008	0.008	0.008	−0.008	0.008	0.008	0.008	0.009	0.009	0.009

T_{90}/K	0	10	20	30	40	50	60	70	80	90
100	0.009	0.011	0.013	0.014	0.014	0.014	0.014	0.013	0.012	0.012
200	0.011	0.010	0.009	0.008	0.007	0.005	0.003	0.001		

$(t_{90}-t_{68})$/°C

t_{90}/°C	0	−10	−20	−30	−40	−50	−60	−70	−80	−90
−100	0.013	0.013	0.014	0.014	0.014	0.013	0.012	0.010	0.008	0.008
0	0.000	0.002	0.004	0.006	0.008	0.009	0.010	0.011	0.012	0.012

t_{90}/°C	0	10	20	30	40	50	60	70	80	90
0	0.000	−0.002	−0.005	−0.007	−0.010	−0.013	−0.016	−0.018	−0.021	−0.024
100	−0.026	−0.028	−0.030	−0.032	−0.034	−0.036	−0.037	−0.038	−0.039	−0.039
200	−0.040	−0.040	−0.040	−0.040	−0.040	−0.040	−0.040	−0.039	−0.039	−0.039
300	−0.039	−0.039	−0.039	−0.040	−0.040	−0.041	−0.042	−0.043	−0.045	−0.046
400	−0.048	−0.051	−0.053	−0.056	−0.059	−0.062	−0.065	−0.068	−0.072	−0.075
500	−0.079	−0.083	−0.087	−0.090	−0.094	−0.098	−0.101	−0.105	−0.108	−0.112
600	−0.115	−0.118	−0.122	−0.125*	−0.08	−0.03	0.02	0.06	0.11	0.16
700	0.20	0.24	0.28	0.31	0.33	0.35	0.36	0.36	0.36	0.35
800	0.34	0.32	0.29	0.25	0.22	0.18	0.14	0.10	0.06	0.03
900	−0.01	−0.03	−0.06	−0.08	−0.10	−0.12	−0.14	−0.16	−0.17	−0.18
1000	−0.19	−0.20	−0.21	−0.22	−0.23	−0.24	−0.25	−0.25	−0.26	−0.26

t_{90}/°C	0	100	200	300	400	500	600	700	800	900
1000		−0.26	−0.30	−0.35	−0.39	−0.44	−0.49	−0.54	−0.60	−0.66
2000	−0.72	−0.79	−0.85	−0.93	−1.00	−1.07	−1.15	−1.24	−1.32	−1.41
3000	−1.50	−0.59	−1.69	−1.78	−1.89	−1.99	−2.10	−2.21	−2.32	−2.43

* A discontinuity in the first derivative of $(t_{90}-t_{68})$ occurs at a temperature of t_{90}=630.6°C when $(t_{90}-t_{68})$= −0.125°C.

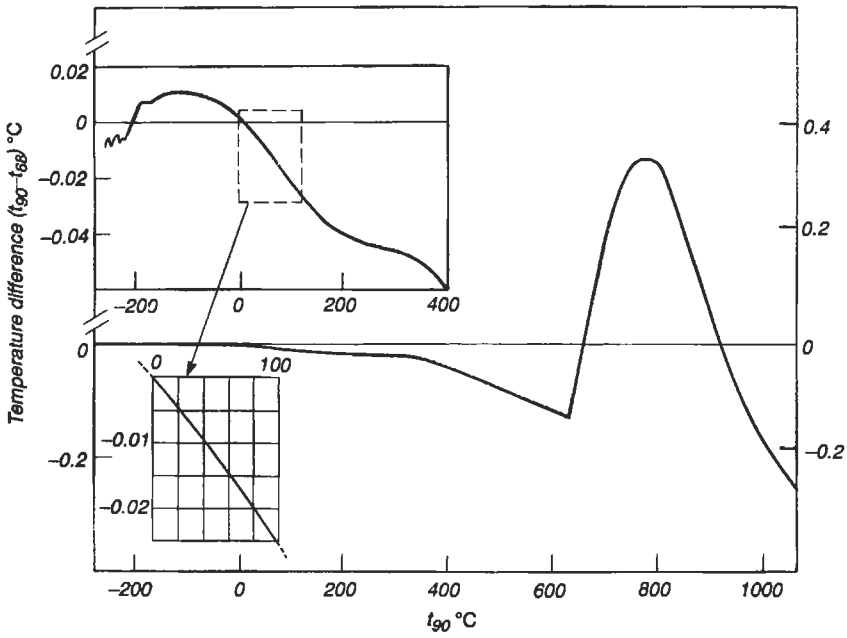


Figure 16.1 *The differences,* $(t_{90}-t_{68})$*, between ITS-90 and IPTS-68 in the range from −260°C to 1 064°C*

Above the freezing point of silver (961.78°C) T_{90} is defined in terms of a defining fixed point and the Planck radiation law.

The defining fixed points of the ITS-90 together with some selected secondary reference points are listed in Table 16.2. Full details of the practical realization of this scale can be found in refs. 2 and 3.

Table 16.2 THE DEFINING FIXED POINTS OF ITS-90 AND SOME SELECTED SECONDARY REFERENCE POINTS

Equilibrium state	T_{90} (K)	t_{90} (°C)
Cd superconducting transition point	0.519	
Zn superconducting transition point	0.851	
Al superconducting transition point	1.179 6	
^{4}He lambda point	2.176 8	
In superconducting transition point	3.414 5	
^{4}He boiling point	4.222 1	
Pb superconducting transition point	7.199 6	
*Triple point of equilibrium hydrogen	13.803 3	
*Boiling point of equilibrium hydrogen at a pressure of 33 330.6 pascals (25/76 standard atmosphere)	17.035 7	
*Boiling point of equilibrium hydrogen	20.271 1	
*Ne triple point	24.556 1	
Ne boiling point	27.098	
*O_2 triple point	54.358 4	−218.791 6
N_2 triple point	63.150	−210.000
N_2 boiling point	77.352	−195.798
*Ar triple point	83.805 8	−189.344 2
O_2 condensation point	90.196	−182.954
Kr triple point	115.776	−157.374
CO_2 sublimation point	194.685	−78.465
*Hg triple point	234.315 6	−38.834 4
H_2O freezing point	273.15	0
*H_2O triple point	273.16	0.01
*Ga melting point	302.914 6	29.764 6
H_2O boiling point	373.124	99.974

Table 16.2 THE DEFINING FIXED POINTS OF ITS-90 AND SOME SELECTED SECONDARY REFERENCE BOOKS *—continued*

Equilibrium state	T_{90} (K)	t_{90} (°C)
*In freezing point	429.748 5	156.598 5
*Sn freezing point	505.078	231.928
Bi freezing point	544.553	271.403
Cd freezing point	594.219	321.069
Pb freezing point	600.612	327.462
*Zn freezing point	692.677	419.527
S boiling point	717.764	444.614
Cu–Al eutectic melting point	821.313	548.163
Sb freezing point	903.78	630.63
*Al freezing point	933.473	660.323
Ag–Cu eutectic melting point	1 053.09	779.94
*Ag freezing point	1 234.93	961.78
*Au freezing point	1 337.33	1 064.18
*Cu freezing point	1 357.77	1 084.62
Ni freezing point	1 728	1 455
Co freezing point	1 768	1 495
Pd freezing point	1 827	1 554
Pt freezing point	2 041	1 768
Rh freezing point	2 235	1 962
Ir freezing point	2 719	2 446
W freezing point	3 693	3 420

* Defining point of ITS-90. For details of experimental techniques used in the realization of these fixed points see references 2 and 3. All except the triple points and the hydrogen boiling point at 33 330.6 Pa are at a pressure of 101 325 Pa (1 standard atmosphere).

16.2 Thermocouple reference tables

The introduction of ITS-90 on 1st January 1990 has led to an international programme, coordinated by the Comité Consultatif de Thermométrie, for the revision of the internationally agreed reference tables for thermocouples. It will take a few years, however, for the new tables to be adopted by national and international standards organizations. Meanwhile the following old tables (BS 4937 and IEC 584-1 1977) based upon IPTS-68 should be used together with the differences $t_{90}-t_{68}$ given in Table 16.1 and Figure 16.1.

Table 16.3 THERMAL ELECTROMOTIVE FORCE (millivolts) OF ELEMENTS RELATIVE TO PLATINUM*

A positive sign means that in a simple thermoelectric circuit the element is positive to the platinum at the reference junction (0°C). The e.m.f. generated by any two elements, A and B, can also be found from this table. It is the algebraic difference, A_e-B_e, between the values (A_e and B_e) for the e.m.f. generated by each relative to platinum; a positive sign indicates that A is positive to B at the reference junction, and a negative sign that A is negative to B.

Cold junction at 0°C

	Temperature of hot junction °C			
	−200	−100	+100	+200
Aluminium	+0.45	−0.06	+0.42	+ 1.06
Antimony	—	—	+4.89	+10.14
Bismuth	+12.39	+7.54	−7.34	−13.57
Cadmium	− 0.04	−0.31	+0.91	+ 2.32
Caesium	+ 0.22	−0.13	—	—
Calcium	—	—	−0.51	− 1.13
Carbon	—	—	+0.70	+ 1.54
Cerium	—	—	+1.14	+ 2.46
Cobalt	—	—	−1.33	− 3.08

* The numerical values given in this table should be taken only as a guide since thermoelectric properties are very sensitive to impurities and state of anneal.

Table 16.3 THERMAL ELECTROMOTIVE FORCE (millivolts) OF ELEMENTS RELATIVE TO PLATINUM*—*continued*

Cold junction at 0°C

	Temperature of hot junction °C			
	−200	−100	+100	+200
Copper	− 0.19	− 0.37	+ 0.76	+ 1.83
Germanium	−46.00	−26.62	+33.9	+72.4
Gold	− 0.21	− 0.39	+ 0.74	+ 1.77
Indium	—	—	+ 0.69	—
Iridium	− 0.25	− 0.35	+ 0.65	+ 1.49
Iron	− 3.10	− 1.94	+ 1.98	+ 3.69
Lead	+ 0.24	− 0.13	+ 0.44	+ 1.09
Lithium	− 1.12	− 1.00	+ 1.82	—
Magnesium	+ 0.31	− 0.09	+ 0.44	+ 1.10
Mercury	—	—	+ 0.06	+ 0.13
Molybdenum	—	—	+ 1.45	+ 3.19
Nickel	+ 2.28	+ 1.22	− 1.48	− 3.10
Palladium	+ 0.81	+ 0.48	− 0.57	− 1.23
Potassium	+ 1.61	+ 0.78	—	—
Rhodium	− 0.20	− 0.34	+ 0.70	+ 1.61
Rubidium	+ 1.09	+ 0.46	—	—
Silicon	+63.13	+37.17	−41.56	−80.58
Silver	− 0.21	− 0.39	+ 0.74	+ 1.77
Sodium	+ 1.00	+ 0.29	—	—
Tantalum	+ 0.21	− 0.10	+ 0.33	+ 0.93
Thallium	—	—	+ 0.58	+ 1.30
Thorium	—	—	− 0.13	− 0.26
Tin	+ 0.26	− 0.12	+ 0.42	+ 1.07
Tungsten	+ 0.43	− 0.15	+ 1.12	+ 2.62
Zinc	− 0.07	− 0.33	+ 0.76	+ 1.89

Table 16.4 THERMAL ELECTROMOTIVE FORCE (millivolts) OF SOME BINARY ALLOYS RELATIVE TO PLATINUM WITH JUNCTIONS AT 0° and 100°C*

Metal A: *Metal B:* %*A*	*Lead Tin*	*Tin Copper*	*Zinc Copper*	*Gold Silver*	*Gold Palladium*	*Nickel Copper*	*Tin Bismuth*	*Antimony Cadmium*	*Antimony Bismuth*
0	+0.44	+0.76	+0.76	+0.74	−0.57	+0.76	−7.34	+ 0.90	−7.34
10	+0.44	+0.53	+0.54	+0.55	−0.85	−2.63	+4.00	+ 1.52	−8.82
20	+0.44	+0.56	+0.53	+0.48	−1.25	−3.08	+3.52	+ 2.88	−7.31
30	+0.44	+0.65	+0.54	+0.47	−1.42	−3.54	+2.56	+ 6.4	−5.66
40	+0.45	+0.65	+0.51	+0.47	−1,69	−4.03	+2.10	+12.2	−4.05
50	+0.45	+0.69	+0.54	+0.48	−2.44	−3.64	+1.77	+23.1	−2.51
60	+0.44	+0.72	+0.47	+0.49	−2.97	−3.06	+1.14	+44.4	−1.06
70	+0.44	+0.62	+0.87	+0.49	−2.63	−2.54	+0.95	+21.5	+0.32
80	+0.43	+0.54	+0.66	+0.50	−0.46	−2.49	+0.78	+12.8	+1.79
90	+0.42	+0.48	+0.98	+0.59	−0.05	−1.93	+0.60	+ 8.1	+3.31
100	+0.42	+0.42	+0.76	+0.78	+0.78	−1.48	+0.42	+ 4.89	+4.89

* The numerical values given in these tables should be taken only as a guide since thermoelectric properties are very sensitive to impurities and state of anneal.

Table 16.5 ABSOLUTE THERMOELECTRIC POWER OF PLATINUM

Temperature (K)	300	400	500	600	700	800	900	1 000	1 100	1 200
Thermoelectric power ($\mu V K^{-1}$)	−5.05	−7.66	−9.69	−11.33	−12.87	−14.38	−15.97	−17.58	−19.03	−20.56

Table 16.6 PLATINUM–10% RHODIUM/PLATINUM THERMOCOUPLE TABLES—TYPE S

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
					e.m.f./μV						
0	0	−53	−103	−150	−194	−236					0
0	0	55	113	173	235	299	365	432	502	573	0
100	645	719	795	872	950	1029	1109	1190	1273	1356	100
200	1440	1525	1611	1698	1785	1873	1962	2051	2141	2232	200
300	2323	2414	2506	2599	2692	2786	2880	2974	3069	3164	300
400	3260	3356	3452	3549	3645	3743	3840	3938	4036	4135	400
500	4234	4333	4432	4532	4632	4732	4832	4933	5034	5136	500
600	5237	5339	5442	5544	5648	5751	5855	5960	6064	6169	600
700	6274	6380	6486	6592	6699	6805	6913	7020	7128	7236	700
800	7345	7454	7563	7672	7782	7892	8003	8114	8225	8336	800
900	8448	8560	8673	8786	8899	9012	9126	9240	9355	9470	900
1000	9585	9700	9816	9932	10048	10165	10282	10400	10517	10635	1000
1100	10754	10872	10991	11110	11229	11348	11467	11587	11707	11827	1100
1200	11947	12067	12188	12308	12429	12550	12671	12792	12913	13034	1200
1300	13155	13276	13397	13519	13640	13761	13883	14004	14125	14247	1300
1400	14368	14489	14610	14731	14852	14973	15094	15215	15336	15456	1400
1500	15576	15697	15817	15937	16057	16176	16296	16415	16534	16653	1500
1600	16771	16890	17008	17125	17243	17360	17477	17594	17711	17826	1600
1700	17942	18056	18170	18282	18394	18504	18612				

Table 16.7 PLATINUM–13% RHODIUM/PLATINUM THERMOCOUPLE TABLES—TYPE R

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
					e.m.f./μV						
0	0	−51	−100	−145	−188	−226					
0	0	54	111	171	232	296	363	431	501	573	0
100	647	723	800	879	959	1041	1124	1208	1294	1380	100
200	1468	1557	1647	1738	1830	1923	2017	2111	2207	2303	200
300	2400	2498	2596	2695	2795	2896	2997	3099	3201	3304	300
400	3407	3511	3616	3721	3826	3933	4039	4146	4254	4362	400
500	4471	4580	4689	4799	4910	5021	5132	5244	5356	5469	500
600	5582	5696	5810	5925	6040	6155	6272	6388	6505	6623	600
700	6741	6860	6979	7098	7218	7339	7460	7582	7703	7826	700
800	7949	8072	8196	8320	8445	8570	8696	8822	8949	9076	800
900	9203	9331	9460	9589	9718	9848	9978	10109	10240	10371	900
1000	10503	10636	10768	10902	11035	11170	11304	11439	11574	11710	1000
1100	11846	11983	12119	12257	12394	12532	12669	12808	12946	13085	1100
1200	13224	13363	13502	13642	13782	13922	14062	14202	14343	14483	1200
1300	14624	14765	14906	15047	15188	15329	15470	15611	15752	15893	1300
1400	16035	16176	16317	16458	16599	16741	16882	17022	17163	17304	1400
1500	17445	17585	17726	17866	18006	18146	18286	18425	18564	18703	1500
1600	18842	18981	19119	19257	19395	19533	19670	19807	19944	20080	1600
1700	20215	20350	20483	20616	20748	20878	21006				

Table 16.8 PLATINUM–30% RHODIUM/PLATINUM–6% RHODIUM THERMOCOUPLE TABLES—TYPE B

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
					e.m.f./μV						
0	0	−2	−3	−2	−0	2	6	11	17	25	0
100	33	43	53	65	78	92	107	123	140	159	100
200	178	199	220	243	266	291	317	344	372	401	200
300	431	462	494	527	561	596	632	669	707	746	300
400	786	827	870	913	957	1002	1048	1095	1143	1192	400
500	1241	1292	1344	1397	1450	1505	1560	1617	1674	1732	500
600	1791	1851	1912	1974	2036	2100	2164	2230	2296	2363	600
700	2430	2499	2569	2639	2710	2782	2855	2928	3003	3078	700
800	3154	3231	3308	3387	3466	3546	3626	3708	3790	3873	800
900	3957	4041	4126	4212	4298	4386	4474	4562	4652	4742	900
1000	4833	4924	5016	5109	5202	5297	5391	5487	5583	4680	1000
1100	5777	5875	5973	6073	6172	6273	6374	6475	6577	6680	1100
1200	6783	6887	6991	7096	7202	7308	7414	7521	7628	7736	1200
1300	7845	7953	8063	8172	8283	8393	8504	8616	8727	8839	1300
1400	8952	9065	9178	9291	9405	9519	9634	9748	9863	9979	1400
1500	10094	10210	10325	10441	10558	10674	10790	10907	11024	11141	1500
1600	11257	11374	11491	11608	11725	11842	11959	12076	12193	12310	1600
1700	12426	12543	12659	12776	12892	13008	13124	13239	13354	13470	1700
1800	13585	13699	13814								

Table 16.9 NICKEL–CHROMIUM/COPPER–NICKEL THERMOCOUPLE—TYPE E (Chrome–Constantan)

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
					e.m.f./μV						
−200	−8824	−9063	−9274	−9.455	−9604	−9719	−9797	−9835			−200
−100	−5237	−5680	−6107	−6516	−6907	−7279	−7631	−7963	−8273	−8561	−100
0	0	−581	−1151	−1709	−2254	−2787	−3306	−3811	−4301	−4777	0
0	0	591	1192	1801	2419	3047	3683	4329	4983	5646	0
100	6317	6996	7683	8377	9078	9787	10501	11222	11949	12681	100
200	13419	14161	14909	15661	16417	17178	17942	18710	19481	20256	200
300	21033	21814	22597	23383	24171	24961	25754	26549	27345	28143	300
400	28943	29744	30546	31350	32155	32960	33767	34574	35382	36190	400
500	36999	37808	38617	39426	40236	41045	41853	42662	43470	44278	500
600	45085	45891	46697	47502	48306	49109	49911	50713	51513	52312	600
700	53110	53907	54703	55498	56291	57083	57873	58663	59451	60237	700
800	61022	61806	62588	63368	64147	64924	65700	66473	67245	68015	800
900	68783	69549	70313	71075	71835	72593	73350	74104	74857	75608	900
1000	76358										

Table 16.10 IRON COPPER–NICKEL THERMOCOUPLE TABLES—TYPE J (Iron–Constantan)

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
					e.m.f./μV						
−200	−7890	−8096									−200
−100	−4632	−5036	−5426	−5801	−6159	−6499	−6821	−7122	−7402	−7659	−100
0	0	−501	−995	−1481	−1960	−2431	−2892	−3344	−3785	−4215	0

Table 16.10 IRON COPPER–NICKEL THERMOCOUPLE TABLES—TYPE J—*continued*
(Iron–Constantan)

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
	e.m.f./μV										
0	0	507	1 019	1 536	2 058	2 585	3 115	3 649	4 186	4 725	0
100	5 268	5 812	6 359	6 907	7 457	8 008	8 560	9 113	9 667	10 222	100
200	10 777	11 332	11 887	12 442	12 998	13 353	14 108	14 663	15 217	15 771	200
300	16 325	16 879	17 432	17 984	18 537	19 089	19 640	20 192	20 743	21 295	300
400	21 846	22 397	22 949	23 501	24 054	24 607	25 161	25 716	26 272	26 829	400
500	27 388	27 949	28 511	29 075	29 642	30 210	30 782	31 356	31 933	32 513	500
600	33 096	33 683	34 273	34 867	35 464	36 066	36 671	37 280	37 893	38 510	600
700	39 130	39 754	40 382	41 013	41 647	42 283	42 922	43 563	44 207	44 852	700
800	45 498	46 144	46 790	47 434	48 076	48 716	49 354	49 989	50 621	51 249	800
900	51 875	52 496	53 115	53 729	54 341	54 948	55 553	56 155	56 753	57 349	900
1 000	57 942	58 533	59 121	59 708	60 293	60 876	61 459	62 039	62 619	63 199	1 000
1 100	63 777	64 355	64 933	65 510	66 087	66 664	67 240	67 815	68 390	68 964	1 100
1 200	69 536										

Table 16.11 COPPER/COPPER–NICKEL THERMOCOUPLE TABLES—TYPE T
(Copper–Constantan)

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
	e.m.f./μV										
−200	−5 603	−5 753	−5 889	−6 007	−6 105	−6 181	−6 232	−6 258			−200
−100	−3 378	−3 656	−3 923	−4 177	−4 419	−4 648	−4 865	−5 069	−5 261	−5 439	−100
0	0	−383	−757	−1 121	−1 475	−1 819	−2 152	−2 475	−2 788	−3 089	0
0	0	391	789	1 196	1 611	2 035	2 467	2 908	3 357	3 813	0
100	4 277	4 749	5 227	5 712	6 204	6 702	7 207	7 718	8 235	8 757	100
200	9 286	9 820	10 360	10 905	11 456	12 011	12 572	13 137	13 707	14 281	200
300	14 860	15 443	16 030	16 621	17 217	17 816	18 420	19 027	19 638	20 252	300
400	20 869										

Table 16.12 NICKEL–CHROMIUM/NICKEL–ALUMINIUM THERMOCOUPLE TABLES—TYPE K
(Chromel–Alumel)

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
	e.m.f./μV										
−200	−5 891	−6 035	−6 158	−6 262	−6 344	−6 404	−6 441	−6 458			−200
−100	−3 553	−3 852	−4 138	−4 410	−4 669	−4 912	−5 141	−5 354	−5 550	−5 730	−100
0	0	−392	−777	−1 156	−1 527	−1 889	−2 243	2 586	−2 920	−3 242	0
0	0	397	798	1 203	1 611	2 022	2 436	2 850	3 266	3 681	0
100	4 095	4 508	4 919	5 327	5 733	6 137	6 539	6 939	7 338	7 737	100
200	8 137	8 537	8 938	9 341	9 745	10 151	10 560	10 969	11 381	11 793	200
300	12 207	12 623	13 039	13 456	13 874	14 292	14 712	15 132	15 552	15 974	300
400	16 395	16 818	17 241	17 664	18 088	18 513	18 938	19 363	19 788	20 214	400
500	20 640	21 066	21 493	21 919	22 346	22 772	23 198	23 624	24 050	24 476	500
600	24 902	25 327	25 751	26 176	26 599	27 022	27 445	27 867	28 288	28 709	600
700	29 128	29 547	29 965	30 383	30 799	31 214	31 629	32 042	32 455	32 866	700
800	32 277	33 686	34 095	34 502	34 909	35 314	35 718	36 121	36 524	36 925	800
900	37 325	37 724	38 122	38 519	38 915	39 310	39 703	40 096	40 488	40 879	900
1 000	41 269	41 657	42 045	42 432	42 817	43 202	43 585	43 968	44 349	44 729	1 000
1 100	45 108	45 486	45 863	46 238	46 612	46 985	47 356	47 726	48 095	48 462	1 100
1 200	48 828	49 192	49 555	49 916	50 276	50 633	50 990	51 344	51 697	52 049	1 200
1 300	52 398	52 747	53 093	53 439	53 782	54 125	54 466	54 807			

Table 16.13 NICKEL–CHROMIUM–SILICON/NICKEL–SILICON (NICROSYL/NISIL) THERMOCOUPLE TABLES—TYPE N

	Reference junction at 0°C										
t_{68}/°C	0	10	20	30	40	50	60	70	80	90	t_{68}/°C
	e.m.f./μV										
−200	−3 990	−4 083	−4 162	−4 227	−4 277	−4 313	−4 336	−4 345			−200
−100	−2 407	−2 612	−2 808	−2 994	−3 170	−3 336	−3 491	−3 634	−3 766	−3 884	−100
0	0	−260	−518	−772	−1 023	−1 268	−1 509	−1 744	−1 972	−2 193	0
0	0	261	525	793	1 064	1 340	1 619	1 902	2 188	2 479	0
100	2 774	3 072	3 374	3 679	3 988	4 301	4 617	4 936	5 258	5 584	100
200	5 912	6 243	6 577	6 914	7 254	7 596	7 940	8 287	8 636	8 987	200
300	9 340	9 695	10 053	10 412	10 773	11 135	11 499	11 865	12 233	12 602	300
400	12 972	13 344	13 717	14 092	14 467	14 844	15 222	15 601	15 981	16 362	400
500	16 744	17 127	17 511	17 896	18 282	18 668	19 055	19 443	19 831	20 220	500
600	20 609	20 999	21 390	21 781	22 172	22 564	22 956	23 348	23 740	24 133	600
700	24 526	24 919	25 312	25 705	26 098	26 491	26 885	27 278	27 671	28 063	700
800	28 456	28 849	29 241	29 633	30 025	30 417	30 808	31 199	31 590	31 980	800
900	32 370	32 760	33 149	33 538	33 927	34 315	34 702	35 089	35 476	35 862	900
1 000	36 248	36 633	37 018	37 403	37 786	38 169	38 552	38 934	39 316	39 696	1 000
1 100	40 076	40 456	40 835	41 213	41 590	41 966	42 342	42 717	43 091	43 464	1 100
1 200	43 836	44 207	44 578	44 947	45 315	45 682	46 048	46 413	46 777	47 140	1 200
1 300	47 502										

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2. 'Supplementary Information for the ITS-90 and Techniques for Approximating the ITS-90', BIPM, Pavillion de Breteuil, F-92312 Sèvres Celex, France, 1990.
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17 Radiating properties of metals

The ability of a surface to radiate energy is governed by the material of which the surface is composed and its physical condition. Any attempt, therefore, to place a numerical value on this radiating ability should be related to a definition of the surface condition. It is usual to choose smooth polished surfaces for this purpose and thus arrive at values which are comparable from one metal to another.

A full radiator (black body) provides a standard of comparison for defining the radiating ability of any other body or surface by determining the ratio of the emission of the surface to that of the black body when they are at the same temperature. An examination of the ratios thus obtained shows that the radiating ability of a metal surface varies with wavelength, temperature and angle of emission. The definition of the emissivity, as the ratio is called, must therefore take into account these variations.

DEFINITIONS OF EMISSIVITY

Special emissivity, ε_λ, of a surface is the ratio of the energy radiated over an infinitesimally small wavelength range at wavelength λ in a specified direction, by unit area of the surface, to the energy radiated by unit area of a full radiator at the same temperature.

The emissivity in a direction normal to the surface is most commonly used, but to avoid confusion it should be called the *normal spectral emissivity*.

Total emissivity, ε_t, is the ratio of the total energy radiated in a specified direction by unit area of the surface to the total energy radiated by a full radiator at the same temperature.

The *normal total emissivity* is most commonly employed.

The *absorptivity* (a) and *reflectivity* (r), for an opaque polished surface, are defined as the ratio of the rate of absorption or reflection of energy to the rate of incidence of energy. Since the incident energy must be either reflected or absorbed the sum of the reflectivity and absorptivity must be unity. Since the absorptivity is equal to the emissivity (ε)

$$\varepsilon = a = 1 - r$$

Hence the emissivity may be derived from the reflectivity and this is sometimes more convenient than a direct determination.

The following equation relates the reflectivity to the refractive index, which is a complex quantity given by $(n - jk)$, where n is the real part and k is the complex part and is usually known as the extinction coefficient:

$$r = \frac{n^2 + k^2 + 1 - 2n}{n^2 + k^2 + 1 + 2n}$$

where the extinction coefficient is such that the fraction of light transmitted perpendicularly through a layer d cm thick is $\exp(-4\pi dk/\lambda)$, λ being the wavelength in air. Hence

$$\varepsilon = 1 - r = \frac{4n}{n^2 + k^2 + 1 + 2n}$$

The Maxwell electromagnetic theory gives

$$2n^2 = \mu\left[e^2 + \frac{\sigma^2\mu_0^2c^4}{4\pi^2\nu^2}\right]^{1/2} + \mu e$$

$$2k^2 = \mu\left[e^2 + \frac{\sigma^2\mu_0^2c^4}{4\pi^2\nu^2}\right]^{1/2} - \mu e$$

where σ is the electrical conductivity, e the dielectric constant (both at frequency ν), μ_0 the permeability of free space ($= 4\pi \times 10^{-7}$ by definition), μ the relative permeability of the metal (≈ 1), and c the velocity in free space.

It follows that for long wavelengths (ν small), where $\sigma\mu_0c^2/2\pi\nu$ is large in comparison with e

$$\varepsilon = c_1(\rho/\lambda)^{1/2} \text{ approx.} \tag{17.1}$$

where ρ is the specific resistance in Ωm, and c_1 a constant of value 0.365 when λ is expressed in metres. Further terms may be added to give a better approximation, thus

$$\varepsilon = c_1(\rho/\lambda)^{1/2} + c_2(\rho/\lambda) + c_3(\rho/\lambda)^{3/2} \tag{17.2}$$

where $c_1 = 0.365$, $c_2 = 0.0667$, and $c_3 = 0.0061$.

The equations show that the spectral emissivity of metals should increase as the wavelength decreases and this is in general agreement with experiment. In all cases, however, there is a lack of concordance between the experimental and theoretical values in the visible and ultraviolet (*see* Figure 17.1 for tungsten).

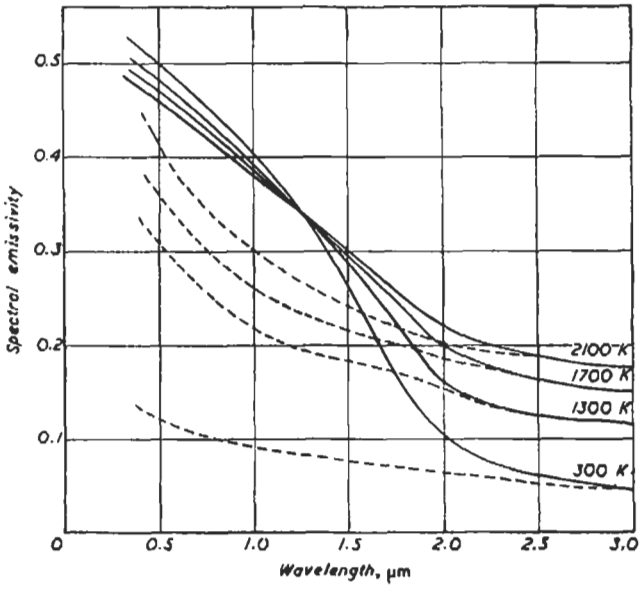


Figure 17.1 *Spectral emissivity of tungsten as a function of wavelength for different temperatures. Dotted lines calculated from equation 17.1. References 1, 2.*

VARIATION OF SPECTRAL EMISSIVITY WITH TEMPERATURE

According to equation 17.1 above, an increase in temperature, since it causes an increase in resistivity, should result in an increase in emissivity. This is generally true in the infra-red region of the spectrum, but in the visible there is often a decrease in emissivity with rise in temperature, as is shown, for example, in Figure 17.1, which gives the variations of spectral emissivity of tungsten with temperature and wavelength. A curious result is shown by these curves: at a wavelength of 1.3 μm there is no variation of emissivity with temperature.

The passage from the solid to the liquid state of a metal does not usually produce a large change in emissivity. The value for platinum, for example, increases by some 15% in the red and even less in the green and violet. For tungsten and molybdenum the change appears to be negligible, but for gold and silver the change in the red is quite marked—from 0.14 to 0.22 for the former and 0.04 to 0.07 for the latter.

VARIATION OF SPECTRAL EMISSIVITY WITH ANGLE OF EMISSION

A radiating surface which obeys Lambert's cosine law gives an intensity of radiation in any given direction which is proportional to the cosine of the angle the direction makes with the normal to the surface. A full radiator obeys the law while metal surfaces do not and since emissivity is defined by comparison with a full radiator, the emissivities must vary with angle of emission. Typical examples of this variation are shown in Figures 17.2 and 17.3.

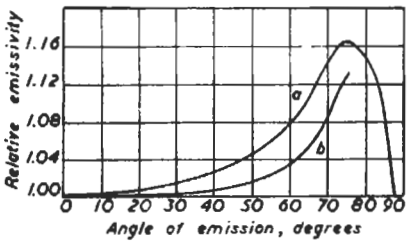


Figure 17.2 *Variation of spectral emissivity of tungsten with angle of emission (a) $\lambda = 0.66\,\mu m$, (b) $\lambda = 0.47\,\mu m$. References 3, 4*

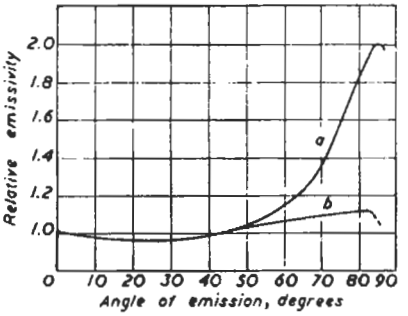


Figure 17.3 *Variation of emissivity of platinum with angle of emission. (a) total emissivity, (b) spectral emissivity in the red. Reference 5*

VARIATION OF TOTAL EMISSIVITY WITH TEMPERATURE

The total emissivity in a particular direction may be expressed in terms of the spectral emissivity in the same direction as follows:

$$\varepsilon_t = \frac{\int_0^\infty E_{\lambda T}\varepsilon_\lambda \, d\lambda}{\int_0^\infty E_{\lambda T}\, d\lambda}$$

where $E_{\lambda T}$ is the energy radiated at wavelength λ and temperature T.

Since, however, complete data on the values of ε_λ throughout the spectrum are not available for many metals, the relation cannot be generally employed. On the basis of this formula and equation 17.2 omitting the third term, the following expression may be derived for the total emissivity

$$\varepsilon_t = K_1\sqrt{(\rho T)} - K_2\rho T$$

where $K_1 = 5.736$ and $K_2 = 1.769$ if ρ is expressed in ohm m.

The expression is in agreement with experiment in so far as it shows an increase of ε_t with T; numerically, however, it does not represent the facts very well, although there is better agreement at low than at high temperatures. This corresponds with what was noted in connection with spectral emissivities where the agreement between experiment and theory is better at long than at short wavelengths: the energy maximum moves towards the short wavelengths as the temperature increases.

VARIATION OF TOTAL EMISSIVITY WITH ANGLE OF EMISSION

The total emissivity of platinum has been measured for different angles of emission (Figure 17.3) and the variations found to be considerably greater than given by similar measurements of spectral emissivity in the visible region. Since the variations of total emissivity with angle of emission are greater the lower the temperature it may be concluded that the variation of spectral emissivity is greater in the infra-red than in the visible.

POLARIZATION OF RADIATION EMITTED BY A METAL SURFACE

The radiation emitted at an oblique angle by a metal surface is found to be polarized. The fraction of polarized light emitted by tungsten at various angles to the normal is shown in Table 17.1. For a circular tungsten filament the total light emitted in a direction normal to the axis includes about 20% of polarized light. Considerable caution must be exercised in interpreting the results obtained from apparatus employing polarizing components when sighting on a metal surface, as, for example, the Wanner pyrometer.

Table 17.1 POLARIZATION OF LIGHT EMITTED BY TUNGSTEN AS A FUNCTION OF THE ANGLE OF EMISSION[4]

Angle of emission (degrees)	0	30	45	60	75	80	85	90
Fraction of light polarized	0	0.10	0.22	0.46	0.75	0.81	0.90	1.00

TEMPERATURE MEASUREMENT AND EMISSIVITY

Radiation pyrometers, both spectral and total, are normally calibrated in terms of full radiation, and when sighted on a metal surface measure a full radiation temperature. The full radiation temperature, T_r, measured by a total radiation pyrometer is related to the true temperature, T, by the formula

$$T_r = T\sqrt[4]{(\varepsilon_t)}$$

where ϵ_t is the total emissivity of the surface.

The spectral or optical pyrometer measures a luminance temperature T_s which is related to the true temperature by the equation

$$\frac{1}{T} - \frac{1}{T_s} = \frac{\lambda \log_e \varepsilon_\lambda}{C_2}$$

where ε_λ is the spectral emissivity and C_2 is the constant in the Wien equation for distribution of energy in the spectrum and has a value of 1.438 cm K. The corrections to be applied to the two types of pyrometer for various emissivities are shown in Figures 17.4 and 17.5. It will be observed that for the same emissivities the correction is considerably greater for total radiation than for spectral radiation. The difference in correction for a total and optical pyrometer sighted on to the same metal surface is even greater, however, since the spectral emissivity in the visible region for a given temperature is always greater than the total emissivity.

EMISSIVITY VALUES

The values of emissivity given in Tables 17.2 to 17.6 relate, as far as is known, to emission from plane polished or plane unoxidized liquid metal surfaces. The radiation emitted will, of course, be increased considerably by oxidation or roughening of the surface. In any practical application, therefore, the values in the tables must be used with discretion, and where precise measurement is of importance a determination of the emissivity should be made for the surface conditions obtaining. As a rough guide the emissivities for various oxidised surfaces are given in Tables 17.5 and 17.6.

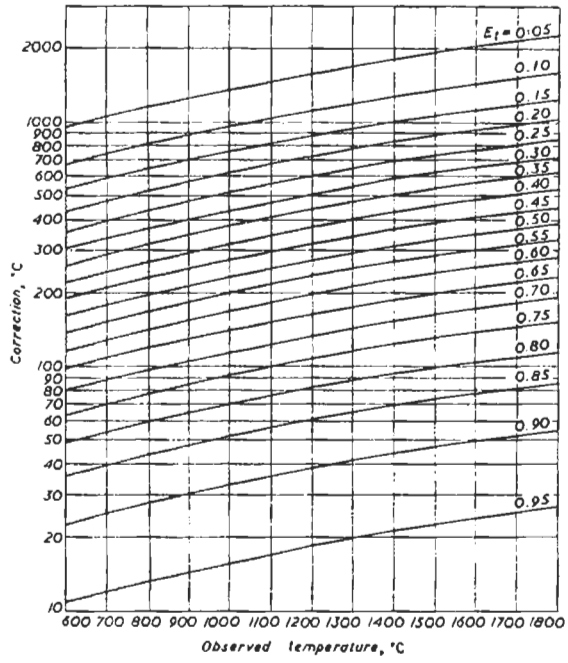


Figure 17.4 *Correction to radiation pyrometer readings for total emissivity*

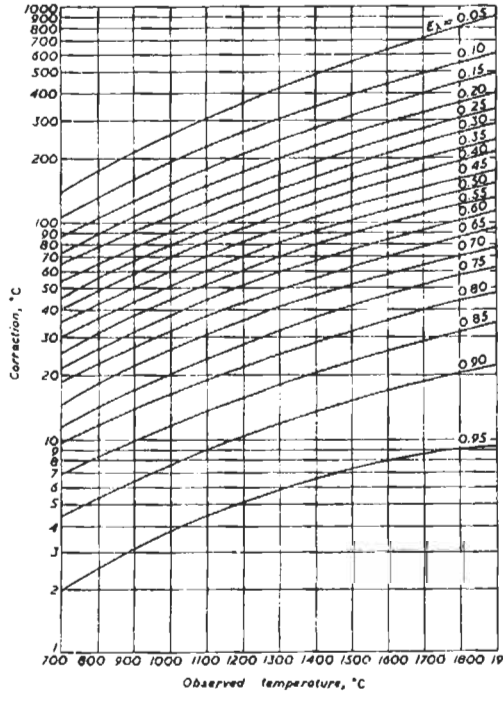


Figure 17.5 *Correction to optical pyrometer readings for spectral emissivity* $\lambda = 0.65\,\mu\text{m}$, $c_2 = 1.438\,\text{cm K}$

Table 17.2 SPECTRAL NORMAL EMISSIVITY OF METALS FOR WAVELENGTH OF 0.65 μm

Metal	*Temperature* °C										*References*
	600	800	1 000	1 200	1 400	1 600	1 800	2 000	2 500	3000	
Beryllium	—	—	0.37	0.37	—	—	—	—	—	—	7
Chromium	—	—	—	—	0.39	—	—	0.39[m]	—	—	8
Cobalt	—	—	0.33–0.38	0.34–0.37	0.35–0.37	0.37[m]	—	—	—	—	8, 9
Copper	—	0.11	0.10	0.10[m]	0.11[m]	0.12[m]	0.14[m]	—	—	—	10
Erbium	—	—	0.55	0.55	0.55	0.38[m]	—	—	—	—	8
Germanium	—	0.55	—	—	—	—	—	—	—	—	11
Gold	0.16–0.18	0.16–0.19	0.16–0.21	0.13[m]	—	—	—	—	—	—	7
Hafnium	—	—	—	—	0.45	—	—	—	—	—	12
Iridium	—	—	0.36	0.34	0.32	—	—	0.30	—	—	8, 13
Iron	—	0.37	0.36	0.35	0.35	0.37[m]	—	—	—	—	7
Manganese	—	—	—	0.59	0.59[m]	—	—	—	—	—	8
Molybdenum	—	0.37–0.43	0.36–0.42	0.35–0.42	0.34–0.41	0.34–0.41	0.33–0.40	0.32–0.39	0.31–0.37	—	7
Nickel	0.36	0.35	0.34	—	—	—	—	—	—	—	7
Niobium	—	—	0.37	0.37	0.37	0.37	0.37	0.37	0.40[m]	—	14
Osmium	—	—	0.52	0.44	0.40	0.38	0.38	0.38	—	—	15
Palladium	—	0.40	0.37	0.34	0.30	0.37[m]	—	—	—	—	16
Platinum	—	0.29–0.31	0.29–0.31	0.29–0.31	0.29–0.31	0.29–0.31	—	—	—	—	7
Rhenium	—	—	—	—	0.42	0.42	0.41	0.41	0.40	—	17
Rhodium	—	0.25	0.22	0.19	0.18	0.16	—	—	—	—	16
Ruthenium	—	—	0.42	0.35	0.32	0.31	0.31	0.31	—	—	15
Silicon	—	0.63	0.57	0.52	0.46	0.48[m]	—	—	—	—	11
Silver	—	0.055	0.055[m]	—	—	—	—	—	—	—	10
Tantalum	0.47	0.46	0.45	0.44	0.42	0.41	0.40	0.39	0.38	0.36	7
Thorium	—	—	0.38	0.38	0.38	—	—	—	—	—	14
Titanium	—	0.48	0.48	0.48	0.47	—	—	—	—	—	18, 19
Tungsten	—	—	0.46–0.48	0.43–0.48	0.42–0.47	0.42–0.47	0.41–0.47	0.40–0.47	0.38–0.46	0.36–0.45	7
Uranium	—	0.19–0.36	0.19–0.36	0.34[m]	0.34[m]	—	—	—	—	—	7
Yttrium	—	—	—	—	0.35	—	—	—	—	—	8
Zirconium	—	—	0.48	0.45	0.42	0.39	0.36	—	—	—	20
Alloys											
Cast iron	—	0.37	0.37	0.37	0.37	0.40[m]	—	—	—	—	—
Nichrome (in hydrogen)	—	0.35	0.35	0.35	0.35	—	—	—	—	—	7
Steel	—	0.35–0.40	0.32–0.40	0.30–0.40	—	0.37[m]	—	—	—	—	7

[m] Value for molten state.

Table 17.3 SPECTRAL EMISSIVITIES IN THE INFRA-RED OF METALS AT HIGH TEMPERATURES

Metal	*Temperature* °C	*Wavelength* μm												*References*
		1.0	1.2	1.4	1.5	1.6	1.8	2.0	2.5	3.0	3.5	4.0	4.5	
Cobalt	800	—	0.26	—	—	—	—	0.21	—	—	—	—	—	7
	1 000	—	0.26	—	—	—	—	0.21	—	0.18	—	—	—	7
	1 200	—	0.26	—	—	—	—	0.22	—	0.19	—	—	—	7
Copper	762	—	—	—	0.031	—	—	0.029	—	—	—	0.025	—	21
	901	—	—	—	0.079	—	—	0.065	0.052	0.043	0.038	0.032	—	22
	985	0.049	—	—	0.037	—	0.034	—	0.032	0.031	—	0.030	—	23
Iridium	827	0.229	0.203	0.185	—	0.167	0.152	0.140	—	—	—	—	—	24
	1 227	0.233	0.213	0.194	—	0.180	0.169	0.160	—	—	—	—	—	24
	1 727	0.243	0.228	0.210	—	0.199	0.188	0.180	—	—	—	—	—	24
	2 127	0.247	0.233	0.219	—	0.207	0.199	0.192	—	—	—	—	—	24
Iron	800	—	0.294	—	—	0.264	—	0.237	0.217	—	—	—	—	25
	1 000	—	0.294	—		0.267	—	0.245	0.227	—	—	—	—	25
	1 200	—	0.291	—	—	0.300	—	0.252	0.235	—	—	—	—	25
	1 245	0.340	0.316	0.298	0.290	0.282	0.268	0.260	0.248	0.240	0.235	0.225	0.218	22
Molybdenum	1 327	0.335	—	—	0.185	—	—	0.140	—	0.115	—	0.114	—	7
	1 727	0.300	—	—	0.195	—	—	0.170	—	0.155	—	0.145	—	7
	2 527	0.260	—	—	0.210	—	—	0.193	—	0.185	—	0.185	—	7
Nickel	800	—	0.295	0.267	—	0.250	0.230	0.215	—	—	—	—	—	25
	1 000	—	0.293	0.269	—	0.252	0.232	0.219	—	—	—	—	—	25
	1 200	—	0.290	0.271	—	0.253	0.235	0.223	—	—	—		—	25
	1 110	—	0.292	0.270	0.250	—	—	0.290	0.205	0.187	0.174	0.162	—	22
Niobium	827	0.345	—	—	0.23	—	—	0.19	—	—	—	—	—	7
	1 227	0.335	—	—	0.25	—	—	0.21	—	—	—	—	—	7
	1 727	0.320	—	—	0.26	—	—	0.23	—	—	—	—	—	7
	2 127	0.315	—	—	0.27	—	—	0.25	—	—	—	—	—	7
Platinum	1 127	—	0.257	—	0.227	—	—	0.193	—	0.151	—	0.130	—	7

Table 17.3 SPECTRAL EMISSIVITIES IN THE INFRA-RED OF METALS AT HIGH TEMPERATURES—*continued*

Metal	*Temperature* C	*Wavelength* μm												*References*
		1.0	1.2	1.4	1.5	1.6	1.8	2.0	2.5	3.0	3.5	4.0	4.5	
Rhenium	1 537	0.36	—	—	0.29	—	—	0.25	0.23	—	—	—	—	17
	2 118	0.36	—	—	0.30	—	—	0.27	0.24	—	—	—	—	17
	2 772	0.36	—	—	0.32	—	—	0.29	0.26	—	—	—	—	17
Tantalum	1 427	0.295	—	—	0.220	—	—	0.190	—	0.170	—	0.150	—	7
	1 927	0.310	—	—	0.245	—	—	0.215	—	0.192	—	0.180	—	7
	2 527	0.330	—	—	0.290	—	—	0.270	—	0.240	—	0.230	—	7
Titanium	750	0.490	—	0.510	0.500	—	—	0.455	—	0.525	0.575	0.600	—	26
Tungsten	1 327	0.385	—	—	0.28	—	—	0.21	—	0.13	—	0.095	—	7
	2 127	0.37	—	—	0.292	—	—	0.245	—	0.18	—	0.15	—	7
	2 527	0.36	—	—	0.30	—	—	0.26	—	—	—	—	—	7
Zirconium	1 127	0.46	—	—	0.422	—	—	0.386	0.360	0.348	—	—	—	27
	1 327	0.444	—	—	—	—	—	0.368	—	0.343	—	0.325	—	27
	1 727	0.442	—	—	0.375	—	—	0.357	0.351	0.342	0.330	—	—	27

Table 17.4 SPECTRAL NORMAL EMISSIVITY OF METALS AT ROOM TEMPERATURE
(Derived from reflectivity data by formula $\varepsilon = 1 - r$)

	Wavelength μm							
Metal	10.0	9.0	5.0	3.0	1.0	0.6	0.5	*References*
Aluminium	0.02–0.04	—	0.03–0.08	0.03–0.12	0.08–0.27	—	—	7
Antimony*	—	0.28	0.31	0.35	0.45	0.47	—	28
Bismuth	0.08	—	0.12	0.26	0.72	0.76	0.75	29
Cadmium	—	0.02	0.04	0.07	0.30	—	—	30
Chromium	—	0.08	0.19	0.30	0.43	0.44	0.45	28
Cobalt	—	0.04	0.15	0.23	0.32	—	—	30
Copper	0.021	—	0.024	0.026	0.030	0.080	0.36	7
Gold	0.015	0.015	0.015	0.015	0.020	0.080	0.45	7
Iridium	—	0.04	0.06	0.09	0.22	—	—	30
Iron	—	—	—	—	0.41	0.48	0.49	16
Lead	—	0.06	0.08	—	—	—	—	31
Magnesium*	—	0.07	0.14	0.20	0.26	0.27	0.28	28
Molybdenum	0.15	—	0.16	0.19	0.42	—	—	32
Nickel	—	0.04	0.06	0.12	0.27	—	—	33
Niobium	0.04	—	0.06	0.14	0.29	0.55	—	7
Palladium	—	0.03	0.10	0.12	0.28	0.37	0.42	20, 16, 34
Platinum	0.05	—	0.06	0.11	0.24	0.36	0.40	35
Rhodium	—	0.05	0.07	0.08	0.16	0.21	0.24	28
Silver	0.02	—	0.02	0.02	0.03	0.03	0.03	7
Tantalum	—	0.06	0.07	0.08	0.22	0.55	0.62	30
Tellurium	—	0.22	0.43	0.47	0.50	0.51	—	28
Tin	—	0.14	0.24	0.32	0.46	—	—	30
Titanium	0.05–0.12	—	0.10–0.18	0.25–0.33	0.37–0.49	—	—	7
Tungsten	0.03	—	0.05	0.07	0.40	0.44–0.49	—	7
Vanadium	0.06–0.09	—	0.07–0.11	0.10–0.17	0.36–0.50	0.42–0.57	0.43–0.59	7
Zinc	0.03	—	0.05	0.08	0.50–0.61	0.42–0.58	—	7

* Values for spectral angular (15°) emissivity only.

Table 17.5 SPECTRAL EMISSIVITY OF OXIDIZED METALS FOR WAVELENGTH OF 0.65 μm
(Oxide formed on smooth surfaces)
(For oxides in the form of refractory materials, values of emissivity widely different from those below may be given and will be dependent on the grain size)

Metal	$\varepsilon_{0.65}$	*Metal*	$\varepsilon_{0.65}$
Aluminium	0.30	Uranium	0.30
Beryllium	0.61	Vanadium	0.70
Chromium	0.60	Yttrium	0.60
Cobalt	0.77	Zirconium	0.80
Copper	0.70		
Iron	0.63		
Magnesium	0.20	*Alloys*	
Nickel	0.85	Cast iron	0.70
Niobium	0.71	Nichrome	0.90
Tantalum	0.42	Constantan	0.84
Thorium	0.57	Carbon steel	0.80
Titanium	0.50	Stainless steel	0.85

References 7 and 8.

Table 17.6 TOTAL NORMAL EMISSIVITY OF METALS

Metal	*Temperature* °C										*References*
	20	100	500	1 000	1 200	1 400	1 600	2 000	2 500	3 000	
Aluminium	—	0.038	0.064	—	—	—	—	—	—	—	36
Beryllium	—	—	—	0.55	0.87	—	—	—	—	—	37
Bismuth	—	0.06	—	—	—	—	—	—	—	—	—
Chromium	—	0.08	0.11–0.14	—	—	—	—	—	—	—	7
Cobalt	—	0.15–0.24	0.34–0.46	—	—	—	—	—	—	—	7
Copper	—	—	0.02	—	0.12[m]	—	—	—	—	—	7
Germanium	—	—	0.54	—	—	—	—	—	—	—	38
Gold	—	0.02	0.02	—	—	—	—	—	—	—	—
Hafnium	—	—	—	—	0.30	0.31	0.32	—	—	—	39
Iron	0.05	0.07	0.14	0.24	—	—	—	—	—	—	7
Lead	—	0.63	—	—	—	—	—	—	—	—	40
Magnesium	—	0.12*	—	—	—	—	—	—	—	—	21
Mercury	—	0.12	—	—	—	—	—	—	—	—	—
Molybdenum	0.065	0.08	0.13	0.19	0.22	0.24	0.27	—	—	—	7
Nickel	—	—	0.09–0.15	0.14–0.22	—	—	—	—	—	—	7
Niobium	—	—	—	0.12	0.14	0.16	0.18	0.21	—	—	41
Palladium	—	—	0.06	0.12	0.15	—	—	—	—	—	16
Platinum	—	—	0.086	0.14	0.16	—	—	—	—	—	7
Rhenium	—	—	—	0.22	0.25	0.27	0.29	—	—	—	42
Rhodium	—	—	0.035	0.07	0.08	0.09	—	—	—	—	16
Silver	—	0.02–0.03	0.02–0.03	—	—	—	—	—	—	—	7
Tantalum	0.03	0.04	0.06	0.11	0.13	0.15	0.18	0.23	0.28	—	7
Tin	—	0.07	—	—	—	—	—	—	—	—	43
Titanium	—	0.11	—	—	—	—	—	—	—	—	44
Tungsten	—	—	0.05	0.11	0.14	0.17	0.19	0.23	0.27	0.30	7
Uranium (α-phase)	—	—	0.33*	—	—	—	—	—	—	—	7
Uranium (γ-phase)	—	—	—	0.29–0.40*	—	—	—	—	—	—	7
Zinc	—	0.07	—	—	—	—	—	—	—	—	45
Zinc (galvanized iron)	—	0.21	—	—	—	—	—	—	—	—	43
Zirconium	—	—	—	0.22	0.25	0.27	—	—	—	—	46
Alloys											
Brass	—	0.059	—	—	—	—	—	—	—	—	43
Cast iron (cleaned)	—	0.21	—	—	—	—	0.29[m]	—	—	—	7
Nichrome	—	—	0.95	0.98	—	—	—	—	—	—	7
Steel (polished)	—	0.13–0.21	0.18–0.26	0.55–0.80	—	—	—	—	—	—	7
Steel (cleaned)	—	0.21–0.38	0.25–0.42	0.50–0.77	—	—	—	—	—	—	7

* Value for total hemispherical emissivity. [m] Value for molten state.

Table 17.7 TOTAL NORMAL EMISSIVITY OF OXIDIZED METALS

The values depend on the degree of oxidation and the grain size.
Unless stated otherwise, the following are results obtained for metals oxidised in general above 600°C.

Metal	200°C	400°C	600°C	800°C	1 000°C	*References*
Alumium	0.11	0.15	0.19	—	—	40
Brass	0.61	0.60	0.59	—	—	40
Chromium	—	0.09	0.14–0.34	—	—	16
Copper (red heat for 30 min)	0.15	0.18	0.23	0.24	—	7
Copper (stably oxidized at 760°C)	—	0.40–0.50	0.60–0.66	—	—	7
Copper (extreme oxidation)	—	0.88	0.92	—	—	7
Cast iron	0.64	0.71	0.78	—	—	40
Cast iron (strongly oxidized)	0.95	—	—	—	—	—
Iron (red heat for 30 min)	0.45	0.52	0.57	—	—	7
Lead	0.63	—	—	—	—	—
Molybdenum (oxide volatile in vacuum above 540°C)	—	0.84	—	—	—	7
Monel	0.41	0.44	0.47	—	—	40
Nickel (stably oxidized at 900°C)	0.15–0.50	0.33–0.51	0.44–0.57	0.49–0.71	—	7
Nimonic (buffed, oxidized at 900°C)	—	0.46	—	—	—	47
Nimonic (buffed, oxidized at 1 200°C)	—	0.72	—	—	—	47
Niobium (oxidized and annealed)*	—	—	—	0.74	—	7
Palladium	0.03	0.05	0.076	—	0.124	16
Stainless steel (stably oxidized at high temperature)	—	0.80–0.87	0.84–0.91	0.89–0.95	—	7
Stainless steel (red heat in air for 30 min)	0.12–0.25	0.17–0.30	0.23–0.37	0.30–0.44	~	7
Stainless steel (buffed, stably oxidized at 600°C)	—	0.41	0.44	0.54	—	7
Stainless steel (polished, oxidized at high temperature)	—	—	0.65–0.70	—	0.73–0.83	7
Stainless steel (shot blasted stably oxidized at 600°C)	—	0.65	0.67	—	—	7
Tantalum (red heat for 30 min)	0.42	0.42	0.42	—	—	7
Zinc	—	0.11	—	—	—	40

* Value for total hemispherical emissivity.

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18 Electron emission

Under normal conditions electrons are prevented from leaving a metal by a potential step at the surface. The height of this potential step is called the work function ϕ. Electrons can, however, escape if they are given enough energy. This energy can be supplied in a number of different ways, giving rise to the various types of electron emission.

18.1 Thermionic emission

When a metal is heated, some electrons with energies near the Fermi level are enabled to escape by acquiring extra thermal energy. An adjacent anode carrying a sufficiently positive potential will collect all the electrons emitted, and the saturated emission current will flow. A further increase of anode potential causes a positive field at the metal surface; this lowers the potential barrier slightly and increases the current. The 'zero field' saturated emission current per unit area of the cathode J, is related to the temperature according to the Richardson–Dushman equation.

$$J = AT^2 \exp(-e\phi/kT)$$

where A is a constant, e the electronic charge, k Boltzmann's constant and T the absolute temperature.

For a metal, the theoretical value of A is $1.2\ \mathrm{MA\,m^{-2}}$. In practice ϕ usually has a temperature coefficient and this results in a different value of A. The work function ϕ cannot be calculated reliably, but tends to increase with the density of the metal. The observed values of A and ϕ are shown in Table 18.1 for polycrystalline surfaces of a number of metals.

Table 18.1 THERMIONIC PROPERTIES OF THE ELEMENTS

Element	A $\mathrm{kA\,m^{-2}\,K^{-2}}$	ϕ V	*Element*	A $\mathrm{kA\,m^{-2}\,K^{-2}}$	ϕ V
Barium	600	2.11	Niobium	1 200	4.19
Beryllium	3 000	3.75	Osmium	1 100 000	5.93
Caesium	1 600	1.81	Palladium	600	4.9
Calcium	600	2.24	Platinum	320	5.32
Carbon	150	4.5	Rhenium	1 200	4.96
Chromium	1 200	3.90	Rhodium	330	4.8
Cobalt	410	4.41	Silicon	80	3.6
Copper	1 200	4.41	Tantalum	1 200	4.25
Hafnium	220	3.60	Thorium	700	3.38
Iridium	1 200	5.27	Titanium	—	3.9
Iron α	260	4.5	Tungsten	600	4.54
Iron γ	15	4.21	Uranium	60	3.27
Molybdenum	550	4.15	Zirconium	3 300	4.12
Nickel	300	4.61			

References: 1, 2, 3, 4 (General); 5 (Hf), 6 (Nb, Ta, Re, Os, Ir); 7 (Be, Cr, Cu).

To calculate the emission from the values of A and ϕ in the table, the emission formula may be written as

$$\log_{10} J = \log_{10} A + 2 \log_{10} T - 5040\phi T^{-1}$$

where J is in $kA\,m^{-2}$, T is in K.

The work function of a metal is lowered when a layer of a more electropositive material is adsorbed on its surface. This increases the thermionic emission, which has a maximum value when the adsorbed layer is approximately monatomic. Table 18.2 shows typical values of thermionic constants for various such surfaces.

Table 18.2 THERMIONIC PROPERTIES OF REFRACTORY METALS WITH ADSORBED ELECTROPOSITIVE LAYERS

Surface	A $kA\,m^{-2}\,K^{-2}$	ϕ V
Tungsten–barium	15	1.56
Tungsten–caesium	32	1.36
Tungsten–cerium	80	2.71
Tungsten–lanthanum	80	2.71
Tungsten–strontium	—	2.2
Tungsten–thorium	30	2.63
Tungsten–uranium	32	2.84
Tungsten–yttrium	70	2.70
Tungsten–zirconium	50	3.14
Molybdenum–thorium	15	2.59
Tantalum–thorium	15	2.52

Reference 8.

The emission may also be increased by a coating of a refractory metallic compound, usually about 100 μm thick. The thermionic emission follows the usual law but in the case of a semiconductor layer the quantities A and ϕ have a different significance. Table 18.3 shows the

Table 18.3 THERMIONIC PROPERTIES OF REFRACTORY METAL COMPOUNDS

Compound	A $kA\,m^{-2}\,K^{-2}$	ϕ V	*Emission* $kA\,m^{-2}$
TaC	3	3.14	3 at 2000 K
TiC	250	3.35	63 at 2000 K
ZrC	3	2.18	40 at 2000 K
ThC_2	5500	3.5	40 at 2000 K
SiC	640	3.5	4 at 2000 K
UC	330	2.9	50 at 2000 K
CaB_6	26	2.9	0.12 at 1670 K
SrB_6	1.4	2.7	0.036 at 1670 K
BaB_6	160	3.5	0.018 at 1670 K
LaB_6	290	2.7	7 at 1670 K
CeB_6	36	2.6	1.7 at 1670 K
ThB_6	5	2.9	0.022 at 1670 K
PrB_6	—	3.12	
NdB_6	—	4.6	
ThO_2	50	2.6	20 at 1900 K
CeO_2	10	2.3	26 at 1900 K
La_2O_3	9	2.5	8 at 1900 K
Y_2O_3	10	2.4	13 at 1900 K
BaO/SrO (oxide cathode)	1–10	1.0	See comments in text

References: 9 (Carbides), 10 (Borides), 11 (Oxides), 12 (UC).

emission constants for various carbides, borides and oxides, and the emission available at a particular operating temperature.

For a thermionic cathode to be technically useful it must have an adequate emission at a temperature where the rate of evaporation is not excessive. This limits the practical cathodes to a relatively small number. Table 18.4 gives the most important of these with their normal maximum operating temperatures and maximum operating emission densities for a generally acceptable life.

Table 18.4 EMISSION AT THE NORMAL MAXIMUM OPERATING TEMPERATURE OF PRACTICAL CATHODES

Cathode	*Operating temperature* K	*Emission* $kA\,m^{-2}$
Tungsten	2500	3
Tantalum	2400	8
Rhenium	2400	0.5
BaO/SrO on nickel d.c.	1100	10
'Oxide cathode' pulse	1100	100
BaO/SrO Ni. Matrix type	1150	20
'L' cathode	1360	30
Impregnated tungsten	1350	50
ThO_2 on W or Ir	1900	10
LaB_6 on Re	1450	0.5
LaB_6 bulk	1900	50
Thoriated tungsten	1900	10

An 'L' cathode consists of a block of porous tungsten, the front emitting surface of which is activated with barium. A reaction between the tungsten and barium oxide at the rear surface produces free barium which diffuses through the porous tungsten.

Impregnated tungsten is a porous tungsten block whose pores are filled with barium calcium aluminate by infiltration in the molten phase at 1700°C. The emitting surface is partly the compound and partly barium activated tungsten.

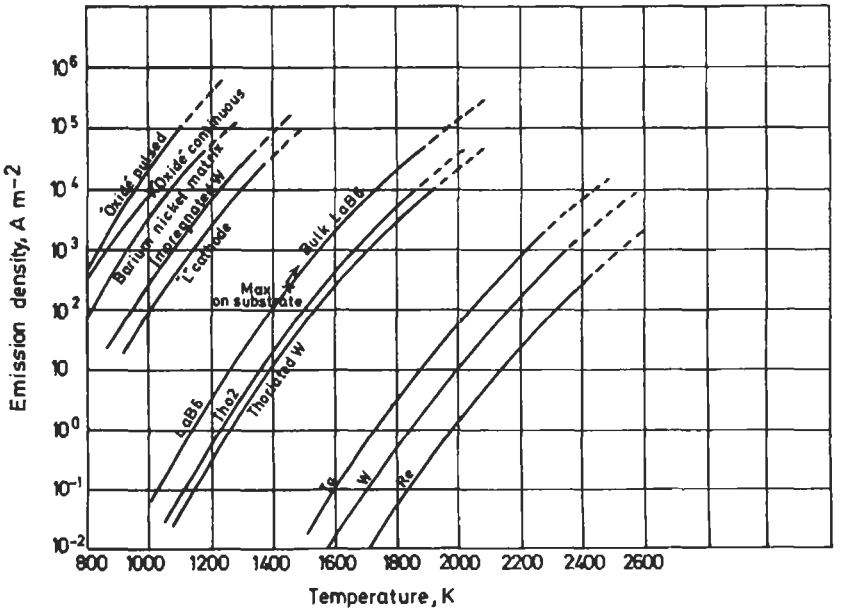


Figure 18.1 *Thermionic emission of practical cathodes as a function of temperature*

The thoriated tungsten is a high density rod or wire containing about 1% thorium oxide. The surface is carburized to form a layer of W_2C. In operation a reaction between the oxide and the carbide produces free thorium, which activates the surface.

Figure 18.1 (reference 13) shows the saturated emissions available from some of these cathodes as a function of temperature. In practice it is usual to operate cathodes at rather less than the saturated emission. The full lines show the region where a useful life is obtainable. The cathode life is usually limited by the evaporation rate and lowering the temperature increases the life considerably. Typically, lowering the temperature of an 'L' or impregnated tungsten cathode by 80 K increases its life by an order.

For an oxide cathode, the continuously drawn emission must be limited to about $10\,kA\,m^{-2}$, but if the current is drawn in microsecond pulses the pulse current may be increased to $100\,kA\,m^{-2}$.

The emissions shown on Figure 18.1 are obtainable only in an environment free from oxidizing gases. In general the partial pressure of gases such as O_2, CO_2, and H_2O should not exceed approximately 10^{-5} Pa. The emission is unaffected by rare gases except when the cathode is bombarded excessively with positive ions; the presence of H_2 may counteract to some extent the effect of oxidizing gases.

18.2 Photoelectric emission

When light of sufficiently high frequency is incident on the surface of a metal, electrons are emitted. In order that electrons shall be emitted with zero velocity from a metal at absolute zero of temperature, the energy of the light photons must equal the energy corresponding to the work function. Thus there is a threshold frequency ν_0 at which $h\nu_0 = e\phi$ where h is Planck's constant. If the frequency of the light is ν, where ν is greater than ν_0, the maximum energy of the emitted electrons is $h\nu - h\nu_0$. At temperatures above absolute zero the threshold is not sharp since light of a frequency less than ν_0 can liberate a small number of electrons. An experiment measuring the energy of photoelectrons emitted for monochromatic light of known energy enables ϕ to be determined fairly accurately, the accuracy improving as the temperature is lowered.

Table 18.5 shows the values of ϕ for a number of metals as determined photoelectrically. The values obtained in this way should correspond to the thermionic values in Table 18.1; discrepancies are probably due to the effect of contamination of the surface, and the photoelectric value is likely to be the more reliable.

Table 18.5 PHOTOELECTRIC WORK FUNCTIONS

Surface	ϕ	*Surface*	ϕ
Aluminium	4.2	Molybdenum	4.2
Antimony	4.1	Nickel	4.9
Arsenic	5.1	Palladium	5.0
Barium	2.5	Platinum	5.3
Beryllium	3.4	Potassium	2.2
Bismuth	4.4	Rhenium	5.0
Boron	4.5	Rhodium	4.6
Cadmium	4.0	Rubidium	2.1
Caesium	1.9	Silicon	4.2
Calcium	2.9	Silver	4.7
Carbon	4.8	Sodium	2.2
Chromium	4.4	Strontium	2.7
Cobalt	4.0	Tantalum	4.1
Copper	4.5	Tellurium	4.8
Gallium	3.9	Thallium	3.8
Germanium	4.8	Thorium	3.5
Gold	4.8	Tin	4.3
Iron	4.4	Titanium	4.1
Iridium	4.6	Tungsten	4.5
Lead	4.0	Uranium	3.6
Lithium	2.4	Zinc	4.3
Manganese	3.8	Zirconium	3.8
Mercury	4.5		

References: 1, 2, 3 (General); 14 (Cu, Ag, Al); 15 (Re).

For practical uses it is required to obtain the maximum photoelectric current for a given light flux. The photoelectric efficiency of a surface may be defined in various ways, the most fundamental being the quantum efficiency Y. This is the ratio of the number of electrons released to the number of incident photons. For clean metals this is very low (10^{-4} approximately) so they are not often used. The efficient photoemitters as used in photocells and photomultipliers are semiconductors with a low effective photon threshold. They are usually formed by combination of one or more alkali metals with an evaporated thin film of antimony (apart from the type consisting of caesium on oxidized silver). Table 18.6 gives the value of maximum photoelectric yields for various such surfaces. This maximum is reached at photon energies 1–1.5 eV above the threshold value, which is also shown.

Table 18.6 PROPERTIES OF EFFICIENT PHOTOELECTRIC EMITTING SURFACE

Surface	*Photoelectric quantum efficiency* Y	*Photon threshold energy* eV
Na_3Sb	0.02	3.1
K_3Sb	0.07	2.6
Rb_3Sb	0.10	2.2
Cs_3Sb	0.25	2.05
NaK_3Sb	0.30	2.0
$CsNaK_3Sb$	0.40	1.55

Reference 16.

The corresponding wavelength of light λ in nm is related to the photon energy $e\phi$ in electron volts by the relationship

$$\lambda = 1.24 \times 10^3 \phi^{-1}$$

18.3 Secondary emission

When electrons (primaries) are incident upon a surface of a solid, electrons (secondaries) are produced which leave the surface in the direction from which the primaries arrive. The total flow of secondaries consists of:

1. Primaries elastically scattered.
2. Primaries reflected inelastically with an energy loss of some tens of volts.
3. True secondaries with an energy independent of the primary energy and a mean value of about 10 eV. Electrons with an energy up to about 50 eV are usually considered to be true secondaries.

The ratio of the total flow of secondaries to that of the primaries is called the secondary emission coefficient δ. As the primary electron energy is increased from zero, δ rises to reach a maximum value δ_{max} for a primary energy V_{max} in the range of 200–1 000 eV for metals, and it falls off more slowly at energies above V_{max}. The shape of the curve relating δ to V is approximately similar for most metals, and a curve normalized to δ_{max} and V_{max} is shown in Figure 18.2.

The values of δ_{max} and V_{max} are shown for most metals in Table 18.7. These values are for clean smooth polycrystalline surfaces. It is impossible to remove oxide films from many metals, such as aluminium or magnesium, by heating. These metals are usually deposited as clean layers either by evaporating in high vacuum or by sputtering. Alternatively the surface of the bulk metal may be cleaned by sputtering in an electric discharge in argon.

It should be noted that the secondary emission is reduced by roughening the surface, as some of the secondaries released in the valleys in the surface may be intercepted by the adjacent high spots. An example of this is carbon; the value of δ_{max} for polished graphite is approximately 1, while that for soot is only about 0.5.

The secondary emission of metal oxides is usually higher than that of metals. Surfaces with high values of δ are used in secondary electron multipliers and are prepared by oxidizing metals containing small quantities, usually about 2%, of magnesium, beryllium or aluminium. Oxidized

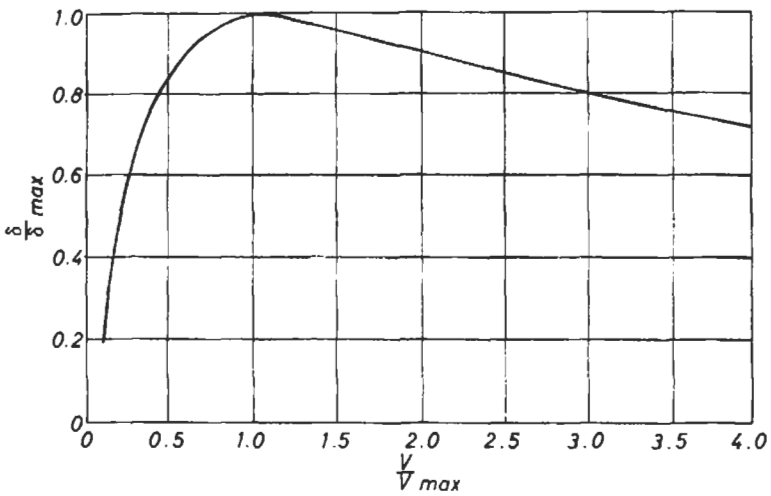


Figure 18.2 *Normalized curve of secondary emission as a function of primary voltage*

Table 18.7 MAXIMUM SECONDARY EMISSION COEFFICIENTS

Element	δ_{max}	V_{max}	*Element*	δ_{max}	V_{max}
Aluminium	0.97	300	Manganese	1.35	200
Antimony	1.30	600	Mercury	1.30	600
Barium	0.85	300	Molybdenum	1.20	350
Beryllium	0.5	200	Nickel	1.35	450
Bismuth	1.15	550	Niobium	1.20	350
Boron	1.2	150	Palladium	1.65	550
Cadmium	1.59	800	Platinum	1.60	720
Calcium	0.60	200	Potassium	0.53	175
Carbon (Graphite)	1.02	300	Rhenium	1.30	800
Caesium	0.72	400	Rubidium	0.90	300
Chromium	1.10	400	Ruthenium	1.40	570
Cobalt	1.35	500	Silicon	1.10	250
Copper	1.28	600	Silver	1.56	800
Dysprosium	0.99	900	Sodium	0.82	300
Erbium	1.05	1 100	Strontium	0.72	400
Gadolinium	1.04	600	Tantalum	1.25	600
Gallium	1.08	600	Terbium	1.02	900
Germanium	1.08	400	Thallium	1.40	800
Gold	1.79	1 000	Thulium	1.05	1 100
Holmium	1.02	900	Thorium	1.10	800
Indium	1.40	500	Tin	1.35	500
Irdium	1.55	700	Titanium	0.90	280
Iron	1.30	200	Tungsten	1.35	650
Lead	1.10	500	Ytterbium	1.04	800
Lithium	0.52	100	Zinc	1.40	800
Magnesium	0.97	275	Zirconium	1.10	350

References: 17; 18 (Pt, Ir, Ru); 19 (Rare earth metals).

metal surfaces with caesium evaporated on to them also have high values of δ and are used in photomultipliers. Table 18.8 shows values of δ obtained from various such surfaces.

Table 18.9 shows the secondary emission from a number of insulating metal compounds either as evaporated films (e) or surface layers on the parent metal (s). These layers must be very thin to avoid accumulating a charge. The secondary electrons originate normally within 10 nm of the surface, so provided films are thicker than this a true value of δ will be obtained.

Table 18.8 SECONDARY EMISSION FROM OXIDIZED ALLOYS AND PHOTOCELL SURFACES

Oxidized alloy	δ_{max}	V_{max}
Ag–Mg	10–16	600
Ag–Be	6	500
Ni–Be	5–10	600
Cu–Be	5	500
Cu–Mg	12.5	900
Cu–Mg–Al	10	700
Photocell surfaces		
Ag–O–Cs	6–10	500
Ni–O–Cs	5.7	500
Ag–O–Rb	5.5	800
Ag–Sb–Cs	8.0	500
Sb–Cs	12	450

Reference 20.

Table 18.9 SECONDARY EMISSION FROM INSULATING METAL COMPOUNDS

Material	δ_{max}	V_{max}
Li F (e)	5.6	—
Na F (e)	5.7	—
NaCl (e)	6–6.8	600
KCl (e)	7.5–8.0	1 500
RbCl (e)	5.8	—
Cs Cl (e)	6.5	—
Na Br (e)	6.25	—
KI (e)	5.6	—
NaI (e)	5.5	—
$Ca F_2$ (e)	3.2	—
$Ba F_2$ (e)	4.5	—
$Mg F_2$ (e)	4.1	410
BeO (s)	3.4–8	200–400
MgO (s)	2.4–17.5	400–1 600
Al_2O_3 (s)	1.5–3.2	350–1 300
Cu_2O (s)	1.19–1.25	440
PbS (s)	1.2	500
MoS_2 (s)	1.10	—
WS_2 (s)	0.96–1.04	—
ZnS (s)	1.8	350
MoO_2 (s)	1.09–1.33	—
Ag_2O (s)	0.90–1.18	—
SiO_2 (e)	2.2	300
Cs_2O (s)	2.3–11	800

Reference 21.

18.4 Auger emission

Auger emission is a byproduct of secondary emission. When the energy distribution of secondaries is examined closely, small peaks can be seen superimposed on the basically smooth curve. These peaks can be made much more obvious by electronic differentiation, and have been shown to originate in Auger transitions, as follows (reference 22). A primary electron removes a secondary electron from an electron shell in an atom. Subsequently another electron in a higher energy shell transfers to the vacancy. The energy thus released is given to a third electron which is emitted. It may be seen that the energy of the third electron is independent of the energy of the primary and is characteristic of three energy levels in the excited surface atom. A large number of these Auger energies have been measured for many elements and they provide identification of the element

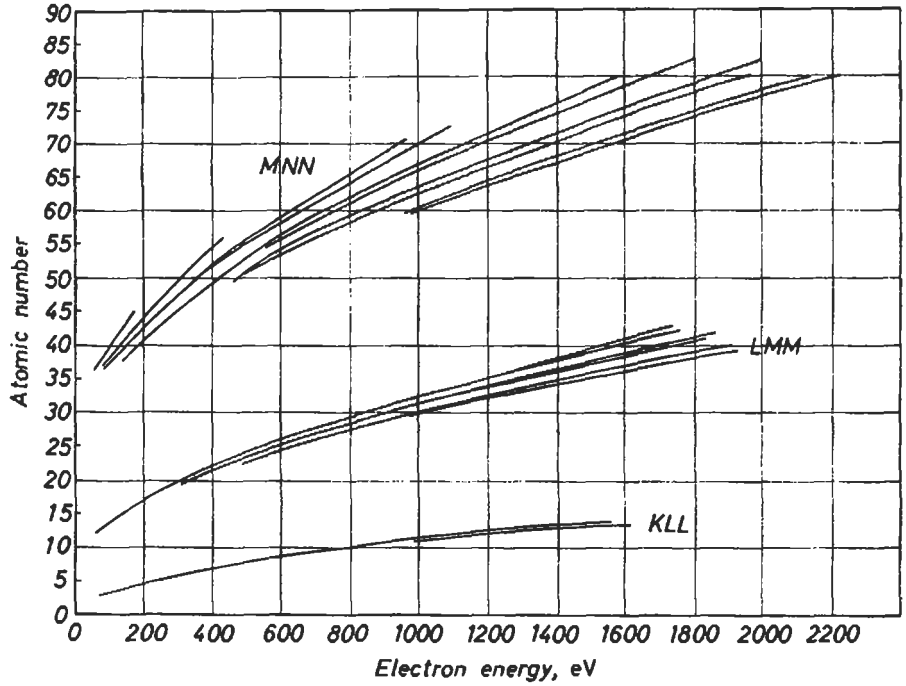


Figure 18.3 *Strongest Auger emission peaks as a function of the atomic number*

concerned. Auger electrons originate within the top 10 nm of the surface and fractions of a monolayer of an element can be detected. This relatively new technique of analysis appears to have a considerable number of possible uses.

The energy of the primary bombarding electrons is usually about 2.5 keV, and the Auger peaks are detected from about 50 eV up to 2 kV. Figure 18.3 shows the Auger energies of the stronger peaks plotted against the atomic number Z. The letters are the electron levels involved in the Auger transition (reference 23).

18.5 Electron emission under positive ion bombardment

When an electrical discharge takes place between two electrodes in a low gas pressure the cathode is bombarded with positive ions and emits electrons. These electrons are essential for maintaining the discharge. The number of electrons released for each arriving ion is usually called γ, the second Townsend coefficient. The coefficient is generally approximately constant for positive ion energies from zero up to about 1 k V. The energy required to release the electron is supplied by neutralization of the positive ion as follows. When the ion is very close to the metal surface the electrostatic is sufficient to extract an electron which neutralizes the positive ion. This releases a photon of energy $(I—\phi)e$, where I is the ionization potential of the gas atom. This photon can then release a photoelectron from the metal provided $(I-\phi)e > \phi e$ or $I > 2\phi$.

The value of γ thus tends to increase with increasing I and decreasing ϕ. Values of γ for various inert gas ions and metals are shown in Table 18.10. At energies above a few keV the value of γ usually increases approximately linearly with energy, the extra electrons being released as a result of kinetic energy transfer.

18.6 Field emission

When a very high positive electric field is applied to the surface of a metal, the potential just outside the metal becomes more positive than the Fermi level in the metal. The work function barrier, instead of being a step becomes very thin, and electrons can 'tunnel' through the barrier

Table 18.10 SECOND TOWNSEND COEFFICIENT γ, ELECTRONS RELEASED PER POSITIVE ION ARRIVING

Metal	*Ion*	γ	*Ion energy* eV
Tungsten (outgassed)	Ne^+	0.25	0–1 000
Tungsten (outgassed)	He^+	0.24	0–1 000
Tungsten (outgassed)	A^+	0.10	0–1 000
Tungsten (outgassed)	Kr^+	0.05	0–1 000
Tungsten (outgassed)	Xe^+	0.02	0–1 000
Tantalum (outgassed)	A^+	0.02	100
Tantalum (gas covered)	He^+	0.2	500
Tantalum (gas covered)	He^{++}	0.7	500
Molybdenum (outgassed)	He^{++}	0.8	0–1 000
	He^+	0.22	0–1 000
	Ne^{++}	0.7	0–1 000
	Ne^+	0.2	0–1 000
	A^{++}	0.35	0–1 000
	A	0.08	0–1 000
	Kr	0.05	0–1 000
Nickel	He^+	0.7	800
	Ne^+	0.4	800
	A^+	0.1	800

Reference 24

and be emitted. This emission is usually called field emission (sometimes tunnel emission), and the emission density is related to the field by the Fowler–Nordheim law. Table 18.11 shows values of $\log_{10}$ (emission density) for various fields for clean tungsten ($\phi = 4.5$ V) and also for a barium contaminated surface ($\phi = 2.0$ V) and an oxygen contaminated surface ($\phi = 6.3$ V).

Table 18.11 FIELD EMISSION FROM TUNGSTEN

$\phi = 2.0$ eV			$\phi = 4.5$ eV			$\phi = 6.3$ eV		
Field 10^9 V m^{-1}	$\log_{10}$ J A m^{-2}	*Current from* 10^{-14} m^2 A	*Field* 10^9 V m^{-1}	$\log_{10}$J A m^{-2}	*Current from* 10^{-14} m^2 A	*Field* 10^9 V m^{-1}	$\log_{10}$ J A m^{-2}	*Current from* 10^{-14} m^2 A
1.0	6.98	1×10^{-7}	2	0.67	4.7×10^{-14}	2	−8.0	10^{-22}
1.2	8.45	2.8×10^{-6}	3	5.57	3.4×10^{-9}	4	3.12	1.3×10^{-11}
1.4	9.49	3.1×10^{-5}	4	8.06	1.1×10^{-6}	6	7.25	1.8×10^{-7}
1.6	10.23	1.9×10^{-4}	5	9.59	3.4×10^{-5}	8	9.34	2.2×10^{-5}
1.8	10.89	7.8×10^{-4}	6	10.62	4.2×10^{-4}	10	10.66	4.6×10^{-4}
2.0	11.40	2.5×10^{-3}	7	11.36	2.3×10^{-3}	12	11.52	3.3×10^{-3}
2.2	11.82	6.6×10^{-3}	8	11.94	8.8×10^{-3}	14	12.16	1.5×10^{-2}
2.4	12.16	1.5×10^{-2}	9	12.39	2.4×10^{-2}	16	12.65	4.5×10^{-2}
2.6	12.45	2.8×10^{-2}	10	12.76	5.8×10^{-2}	18	13.04	1.1×10^{-1}
			12	13.32	2.1×10^{-2}	20	13.36	2.3×10^{-1}

Reference 25.

High fields which produce appreciable emissions usually result from field concentration at the tips of small projections, spikes or whiskers on metal surfaces. As these usually have submicron tip diameters the emission current in A for an area of 10^{-14} m^2 is also shown in Table 18.11.

The field at the tips of emitting projections is greater than the 'macroscopic' field at an electrode by a factor usually called β. This varies between about 1000 for a rough surface, down to less than 100 for a highly polished and voltage conditioned hard metal surface. When the field emission from a projection reaches an appreciable fraction of an ampere, the projection will melt and vaporize and this may initiate electrical breakdown between the electrodes in vacuum. Alternatively the field emission may heat the anode electrode and release gas or metal vapour which can also initiate a breakdown. From Table 18.11 the necessary tip field is likely to be $2 \times 10^9 - 10^{10}$ V m^{-1}, depending on work function while the macroscopic field will usually be of the order of 1% of this.

Single field emitting sources can be made, consisting of a point 0.1–1.0 μm diameter etched on the end of a refractory metal wire. An anode electrode near the point and carrying a positive potential of a few kV is sufficient to cause field emission. The point usually emits over most of its approximately hemispherical tip. The intensity of the emission varies with direction, as different crystal planes on its surface have different work functions (reference 25). The close packed planes, e.g. the (110) plane of a body centred crystal such as tungsten, have the highest work function and lowest field emission. This effect is shown visually by allowing the electrons to strike a hemispherical fluorescent screen around the point. This arrangement has been used extensively to study surface migration and adsorption phenomena. Measurements can however only be carried out in ultra high vacuum (pressure $< 10^{-7}$ Pa) otherwise positive ions are formed in the gas and these quickly destroy the point by ion bombardment.

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19 Electrical properties

19.1 Resistivity

The resistivities of a number of pure metals and alloys are given in Tables 19.1 to 19.4. Resistivity varies with the condition of the material and is sensitive to purity. In general, cold working increases and annealing decreases the resistivity. Common reactive gases such as oxygen, nitrogen and hydrogen may also affect the resistivity, either through selective chemical action with existing metallic impurities (which may even reduce the resistivity) or through solution in the host matrix itself.[1] Thermal cycling through phase transformation, quenching from high temperatures and irradiation, all introduce lattice defects which increase resistivity. These defects include vacancies, dislocations and interstitial atoms. Annealing will promote the movement and eventual removal of these defects. This recovery generally takes place in discrete stages at certain temperatures corresponding to the annealing out of each type of defect. Recovery is complete after treatment at the recrystallization temperature.

Resistivity is often expressed approximately as the sum of the residual resistivity at absolute zero (arising from impurities and lattice defects) and a temperature-dependent intrinsic resistivity (arising from the effect of lattice vibrations upon conduction electrons). The form of temperature dependence is complex, and theories governing it in both solid and liquid metals have been recently discussed in, for example, references 2–15. Over a limited temperature interval, resistivity may be conveniently expressed as a linear relation of the form $\rho_1 = \rho_0 (1 + \alpha T)$, where T is the interval between two temperatures T_1 and T_0, and α is the temperature coefficient of resistivity (TCR). In Table 19.1, TCR values are given for the temperature range 273–373 K, except for some lower-melting-point elements as indicated.

Table 19.1 RESISTIVITY AND TEMPERATURE COEFFICIENT OF PURE METALS

	Room temperature			*Melting point*			
Element	*Temp.* K	*Resistivity* $10^{-8}\,\Omega$m	*TCR* $10^{-3}\,K^{-1}$	*Temp.* K	*Resistivity* $10^{-8}\,\Omega$m *Solid*	*Liquid*	*Ref.*
Aluminium	293	2.61	4.2	933	—	24.2	7, 16
Americium	300	68.9	—	—	—	—	17
Antimony	293	37.6	5.1	913*	—	113.5	7, 18
Arsenic	293	31	—	—	—	—	19
Barium	300	34.3	5.0	1002	276	306	20
Beryllium	300	3.76	8.0	—	—	—	20
Bismuth	293	115	4.6	573*	—	128	7, 18
Cadmium	293	6.6	4.3	603*	—	33.7	7, 21
Caesium	300	21.04	5.3†	301.6	21.2	36.9	22
Calcium	300	3.45	3.7	1113	14.5	33.0	20
Cerium	293	75	0.9	1068	—	125	23, 24
Chromium	300	12.9	5.9	2148	—	80	25, 26
Cobalt	293	5.2	6.6	1766	—	100	26, 27
Copper	293	1.58	4.3	1356	—	20	26, 27
Dysprosium	293	97	—	—	—	—	23
Erbium	293	80	—	—	—	—	23
Europium	293	116	—	1099	188	244	23, 24
Francium	300	34	7.2†	300.2	34	55	22

Table 19.1 RESISTIVITY AND TEMPERATURE COEFFICIENT OF PURE METALS—*continued*

	Room temperature			*Melting point*			
Element	*Temp.* K	*Resistivity* $10^{-8}\,\Omega m$	*TCR* $10^{-3}\,K^{-1}$	*Temp.* K	*Resistivity* *Solid*	$10^{-8}\,\Omega m$ *Liquid*	*Ref.*
Gadolinium	293	132	—	1585	—	195	23, 24
Gallium	293	13.65	—	303	—	25.9	28, 29
Gold	293	2.01	4.0	—	—	—	27
Holmium	293	87	—	—	—	—	23
Indium	293	8.0	5.2	430	—	33.1	7, 30
Iridium	300	5.0	4.5	—	—	—	25
Iron	300	9.8	6.5	1808	—	140	25, 26
Lanthanum	293	62	2.2	1193	—	140	23, 24
Lead	293	19.3	4.2	673*	—	95	7, 31
Lithium	300	9.55	4.0	454	15.6	24.8	22
Lutetium	293	67	—	1925	—	224	3, 23
Magnesium	300	4.51	3.7	—	—	—	20
Manganese	293	143.5	0.4	1517	—	180	26, 32
Mercury	293	94.1	1.0‡	253	—	91	7, 31
Molybdenum	300	5.3	4.35	—	—	—	25
Neodymium	293	64.5	—	—	—	—	23
Nickel	293	6.2	6.8	1725	—	85	26, 27
Niobium	293	13.27	2.6	—	—	—	33
Osmium	293	8.4	4.1	—	—	—	27
Palladium	300	10.5	4.2	1825	48	83	25, 34
Platinum	300	10.4	3.9	2042	—	90	25, 26
Potassium	300	7.47	6.0†	336.4	9.22	13.95	22
Praseodymium	293	66	—	—	—	—	23
Protactinium	298	19.3	—	—	—	—	17
Radium	300	88	6.5	—	—	—	20
Rhenium	293	16.9	4.5	—	—	—	27
Rhodium	293	4.37	4.4	—	—	—	27
Rubidium	300	13.32	6.3†	312.6	14.2	22.5	22
Ruthenium	293	6.7	4.1	—	—	—	27
Samarium	293	86	—	—	—	—	23
Silver	300	1.47	4.1	1234	—	28.5	26, 27
Sodium	300	4.93	5.3†	371	6.86	9.43	22
Strontium	300	13.5	3.2	1042	65.6	84.8	20
Tantalum	300	13.1	3.5	—	—	—	25
Terbium	293	107	—	—	—	—	23
Thallium	293	15.0	5.2	576	—	73.1	7, 31
Thorium	293	14.2	4.0	—	—	—	35
Thulium	293	95	—	—	—	—	23
Tin	293	10.1	4.6	—	—	—	36
Titanium	293	39	3.8	1941	—	400	2, 27
Tungsten	300	5.3	4.8	—	—	—	25
Uranium	293	24.8	2.5	—	—	—	37
Vanadium	300	19.9	3.9	2163	—	200	25, 26
Ytterbium	293	29	—	1097	74	109	5, 23
Zinc	293	5.45	4.2	693	—	37.4	7, 38
Zirconium	293	38.9	4.4	—	—	—	27

* Liquid resistivity at temperature above melting point.
† TCR for the interval 250–300 K.
‡ TCR for the liquid phase.

Resistivity values given in Table 19.1 are for bulk material. If the metal is deposited as a thin film, resistivity may deviate from the bulk value, being affected by parameters such as film thickness and grain size. Many recent investigations have been made on these effects (*see* references 39–41).

The resistivity and temperature coefficient of alloys is often dependent upon the method of preparation and heat treatment. The values given in Table 19.2 relate to particular samples and should not be assumed to apply accurately to other samples of similar composition. In systems which exhibit complete mutual solid solubility, there is often a resistivity maximum near 50/50 composition (e.g. Figure 19.1). The transition elements show complex resistivity and TCR behaviour upon alloying. Very low TCRs, which may be of importance industrially, are obtained in some quaternary Ni–Cr alloys after suitable heat treatment. TCR values given here are for the temperature interval 273–373 K.

Theoretical predictions for the resistivity of alloys have recently been discussed in references 42–46.

Table 19.2 RESISTIVITY AND TEMPERATURE COEFFICIENT OF SOME ALLOYS

Alloy		*Nominal composition* wt. %†	*Temperature* K	*Resistivity* $10^{-8}\ \Omega m$	*TCR* $10^{-3}\ K^{-1}$
Ag–Au	(normal silver)	Au 0.37	293	1.77	—
		Au 10	293	3.6	—
Ag–Cd–Zn–Cu		Cd 18 Zn 16.5 Cu 15	273	7.0	—
Ag–Cu	(standard silver)	Cu 7.5	293	1.9	—
		Cu 10–50	293	2.0–2.1	—
Ag–Cu–Zn		Cu 25 Zn 15	273	8.3	—
Ag–Mn*		Mn 6	293	14	0.2
		Mn 10	293	27	0.02
		Mn 12	293	33	−0.01
		Mn 16–20	293	42–46	−0.03
Ag–Pd		Pd 5	293	3.8	—
		Pd 10	293	5.8	—
		Pd 20	293	10.1	—
Al–Cu etc.		Cu 6	273	3.1	3.8
	(Duralumin)	Cu 4 Mn 0.6 Mg 0.6	293	5.0–5.3	2.3
		Cu 4.1 Mn 0.5 Mg 1.4 Fe 0.2	273	4.0–4.4	—
Al–Mg etc.		Mg 10	273	8.0	—
		Mg 4.75 Mn 0.63 Fe 0.2 Cr 0.13	273	5.66	—
Al–Mg–Si		Mg 0.5 Si 0.5	293	3.25	3.6
Al–Mn		Mn 1.25	293	3.4–4.4	—
Al–Si		Si 12	273	4.5	—
Al–Zn–Mg etc.		Zn 3.6 Mg 2.55 Mn 0.2 Cr 0.2	273	4.75	—
		Zn 5.6 Cu 1.6 Mg 2.5	273	3.7–5.0	
Au–Ag		Ag 10	273	6.3	1.2
		Ag 33	273	10.8	0.65
Au–Co		Co 2.5	293	32.6	—
Au–Cr–Co		Cr 2.1 Co 0.25	293	39.8	+0.02
		Cr 2.1 Co 0.5	293	44.7	−0.06
		Cr 4.2 Co 0.4	293	57.8	−0.08
Au–Cr–Pd		Cr 2.1 Pd 3.5	293	36.9	0±0.02
		Cr 2.1 Pd 9	293	38.7	0±0.02
Au–Cr–Pt		Cr 2.1 Pt 2	293	34.7	0.07
		Cr 2.1 Pt 6	293	25.6	0.19
Au–Cu–Ag		Cu 78.3 Ag 14.3	273	3.6	1.8
		Cu 26.5 Ag 15.2	273	13.2	0.57
		Cu 15.5 Ag 18.1	273	14.6	0.53
Bi–Sn		Sn 2	273	24.4	—
		Sn 90.5	285	16	—
Bi–Sn–Pb	(Rose's metal)	Sn 23 Pb 28	273	64	2.0
	(Wood's metal)	Sn 12.5 Pb 25	273	52	2.0
Cr–Au[47]		Au 0.6 at %	300	19.2	—
Cu–Al		Al 3	273	8.3	1.0
		Al 10	273	12.6	3.2
Cu–Be		Be 2 (+Ni)	273	6.8–7.4	1.0–1.8
Cu–Mn*		Mn 0.98	273	4.83	—
		Mn 1.49	273	6.66	—
		Mn 4.2	293	17.9	0.25
		Mn 7.4	293	19.7	0.17

* TCR applies over a restricted range at room temperature.
† Unless stated otherwise.

Table 19.2 RESISTIVITY AND TEMPERATURE COEFFICIENT OF SOME ALLOYS—*continued*

Alloy		*Nominal composition* wt. %†	*Temperature* K	*Resistivity* 10^{-8} Ωm	*TCR* 10^{-3} K^{-1}
Cu–Mn–Al*		Mn 9 Al 3	293	38	0.010
		Mn 9 Al 5	293	42	0.012
		Mn 12 Al 3	293	48	−0.005
Cu–Mn–In*		Mn 12 In 1·3	293	42.5	0±0.010
Cu–Mn–Fe*		Mn 23.2 Fe 6.2	273	77	0.01
		Mn 14.76 Fe 0.33	293	53.5	—
		Mn 7.1 Fe 1.9	273	20	0.1
Cu–Mn–Ni*		Mn 72 Ni 10	293	175	1.4
		Mn 24 Ni 3	273	48	−0.03
	(Manganin)	Mn 12 Ni 4	293	44	0.00
Cu–Ni		Ni 45 at %	293	49	0±0.02
(*see* Figure 19.1)		Ni 30 at %	293	36.3	0.05
		Ni 20 at %	293	26.6	0.24
		Ni 10 at %	293	14.1	0.52
Cu–Ni–Fe[48]		Ni 45 Fe 2 at %	300	44	—
		Ni 51 Fe 1 at %	300	48	—
Cu–P		P 0.48	293	8.4	0.84
		P 0.93	293	15.2	0.50
Cu–Sn etc.		Sn 12	293	18	0.5
		Sn 5	273	9.5	—
		Sn 6 Zn 4	288	13.5	—
		Sn 5 Zn 5 Pb 5	273	10.5	—
		Sn 5 Ni 5 Zn 2	273	10.5–14	—
Cu–Zn etc.		Zn 10	293	3.8	—
		Zn 15	273	4.65	—
		Zn 30	273	6.65	1.6
		Zn 40	273	6.81	1.7
		Zn 39 Fe 1 Sn 1	273	7.03	—
	(German silver)	Zn 41 Ni 9 Pb 2	293	30.5	—
	(Admiralty brass)	Zn 27.6 Sn 1	273	6.93	—
Cu–Zn–Ni		Zn 32 Ni 8	273	72	—
		Zn 24 Ni 18	273	30.9	0.04
		Zn 26 Ni 30	273	47.6	0.04
		Zn 25 Ni 14	293	33	0.40
Fe–C etc.	(Mild steel)	C 1 Si 1.8	291	12.0	—
	(Cast iron)	C 3.4	293	66.0	—
Fe–Cr		Cr 20	293	62	—
		Cr 12	293	60	—
Fe–Cr–Ni etc.		Cr 18 Ni 8	293	73	—
		Cr 25 Ni 12	293	87	—
		Cr 25 Ni 20	293	88	—
		Cr 18 Ni 37	293	108	—
		Cr 17.7 Ni 7.4 Al 1.2 Mo 0.7 Si 0.4	273	71–102	—
		Cr 18.4 Ni 9.7 Mn 1.4 Si 0.6	273	70.4	—
		Cr 17.9 Ni 9.8 Mn 1.4 Si 0.6 Ti 0.4	273	73.9	—
		Cr 17.7 Ni 12.2 Mo 2.8 Mn 1.5 Si 0.7	273	76.5	—
		Cr 17.5 Ni 13.1 Mo 2.7 Mn 1.7 Si 0.4	273	71.8	—
		Cr 17.4 Ni 13.3 Mo 2.9 Mn 1.5 Si 0.5	273	77.6	—
		Cr 17 Ni 12.8 Mo 2.7 Mn 1.5 Si 0.4	273	75.0	—

* TCR applies over a restricted range at room temperature.
† Unless stated otherwise.

Table 19.2 RESISTIVITY AND TEMPERATURE COEFFICIENT OF SOME ALLOYS—*continued*

Alloy		*Nominal composition* wt. %†	*Temperature* K	*Resistivity* 10^{-8} Ωm	*TCR* $10^{-3}K^{-1}$
Fe–Ni		*See* Figures 19.2 and 19.3	—	—	—
Fe–Ni–Co		Ni 29 Co 17	293	49	3.7
Fe–Si		Si 25	293	45	
		Si 4	293	62	8.0
Fe–Ti etc.		Ti 2.5 C 0.15	293	16	—
Fe–V etc.		V 5 C 1.1	293	121	—
Fe–W etc.		W 20 C 0.2	293	24	—
		W 5 C 0.2	293	20	—
Mg–Al–Zn		Al 9 Zn 2	273	16	—
		Al 4.9 Zn 0.9	273	11.3	—
Na–K liquid[42,50]		K 20 at %	373	28.0	—
		K 40 at %	373	38.2	—
		K 60 at %	373	40.8	—
		K 80 at %	373	33.3	—
Ni–Al etc.		Al 50 at %[49]	300	9.3	—
		Al 2 Mn 2.5 Fe 0.5 Si 1	273	33.3	1.2
		Al 1.6 Si 1.2 Fe 0.1	273	28.1	2.4
Ni–Co–Cr etc.	‡(Udimet 700)	Co 19 Cr 15.2 Mo 5 Al 4.4 Ti 3.4 Fe 0.1	273	131.5	—
Ni–Cr[51]		Cr 5.5 at %	273	41	—
		Cr 11.5 at %	273	70	—
		Cr 27 at %	273	110	—
Ni–Cr etc.	‡(Evanohm)	Cr 20 Al 2.5 Cu 2.5	293	133	0.00
	‡(Karma)	Cr 20 Al 2.5 Fe 2.5	293	134	0.00
		Cr 15 Fe 7	273	98	—
		Cr 20 Fe 5–10	293	109	—
	‡(Hastelloy X)	Cr 22 Fe 20 Mo 9 C 0.15	273	113.8	—
	‡(Inconel X)	Cr 15.4 Fe 6.9 Ti 2.5 Al 0.9	273	124	—
		Cr 9.46 Fe 0.2 Si 0.4	273	70	0.4
Ni–Cu etc.	‡(Monel)	Cu 30 Fe 1.4 Mn 1	273	48	1.9
Ni–Mn		Mn 5	273	18	—
Ni–Mo–Fe		Mo 32 Fe 6	273	135	—
Pb–Sb		Sb 6	273	23	—
Pb–Te–Cu		Te 0.04 Cu 0.06	273	20	—
Pt–Ir		Ir 10	273	24.8	1.3
Pt–Rh		Rh 10	273	18.7	1.66
		Rh 13	273	19.0	1.56
Rh–Co[52]		Co 11 at %	4.2	3.07	—
		Co 20 at %	4.2	4.96	—
		Co 42 at %	4.2	18.98	—
Sn–Pb		Pb 10	288	13.5	—
		Pb 40	273	15	—
		Pb 66.7	288	16	—
Ti–Al–V etc.		Al 6.2 V 4 Fe 0.13	273	167.5	—
Ti–V–Cr–Al etc.		V 13.1 Cr 10.8 Al 3 Fe 0.17	273	149.2	—
Zn–Cu		Cu 1.05	273	6	—
Zn–Al–Cu etc.[53]		Al 4.1 Cu 3.1 Mg 0.05	295	7.2	—

† Unless stated otherwise.

‡ Karma is a trade name of British Driver Harris Co. Ltd.
Inconel and Monel are trade names of Henry Wiggin Co. Ltd.
Udimet is a trade name of Special Metals Corp.
Evanohm is a trade name of Wilbur B. Driver Co.
Hastelloy is a trade name of Cabot Corporation.

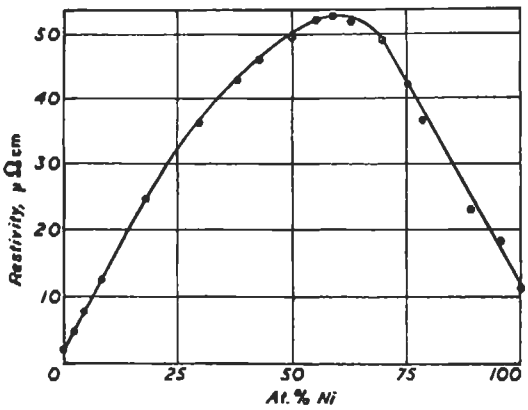


Figure 19.1 *Resistivity of copper-nickel alloys*

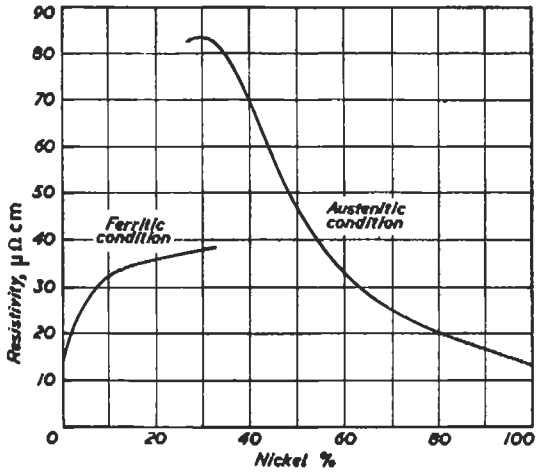


Figure 19.2 *Electrical resistivity of nickel–iron alloys*

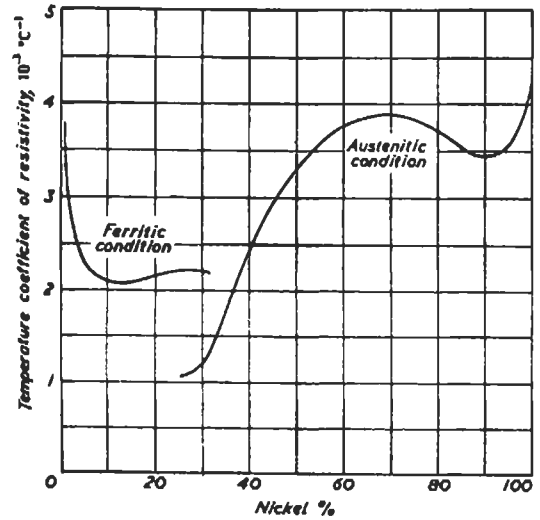


Figure 19.3 *Temperature coefficient of electrical resistivity of nickel–iron alloys*

Dilute copper and aluminium alloys have important applications as electrical conductors. Table 19.3 lists specified resistivity values for certain copper alloys (*see* references 54–56). Table 19.4 shows the effect on the resistivity of EC aluminium (99.45 wt% Al) of the addition of 1 at.% of various solutes. When considering aluminium as an electrical conductor, it is important to achieve strengthening by the addition of suitable solutes without undue reduction in conductivity. The least detrimental additions form intermetallic compounds that remain out of solid solution (*see* references 57 and 57A).

Table 19.3 RESISTIVITY OF SOME SPECIFIC COPPER ALLOYS

Alloy No	*Composition or description*	*Resistivity at* 293 K 10^{-8} Ωm
101, 102	OFHC	1.55–1.58
110	ETP	1.56–1.65
122	phos. deox.	2.0–2.1
220	10% Zn	3.8–3.9
510	5% Sn	10.5–11.5
706	10% Ni	16.5–19.0

Table 19.4 EFFECT ON THE RESISTIVITY OF EC ALUMINIUM OF SOME ADDITIONAL ELEMENTS

Added element 1 at.%	*Increase in resistivity at* 293 K 10^{-8} Ωm
Antimony	0.238
Cerium	0.049
Gadolinium	0.40
Hafnium	2.20
Lanthanum	0.147
Molybdenum	2.04
Niobium	0.44
Tantalum	1.32
Thorium	0.265
Tungsten	7.4
Yttrium	0.255
Zirconium	0.988
Resistivity of EC aluminium 2.694×10^{-8} Ωm	

19.2 Superconductivity

Below a transition temperature T_c some elements, compounds and alloys become superconducting. In this state they exhibit zero electrical resistance and some become perfectly diamagnetic. The application of a magnetic field whether applied externally or generated by a current passing along the superconductor in excess of a critical or limiting value restores the material to its normal resistive state.

Table 19.5 lists the elements which become superconducting when cooled to a sufficiently low temperature together with their transition temperatures and critical fields at 0 K (H_0).[58, 60] The critical field H_c at temperature T is closely represented by the relationship

$$H_c = H_0\left[1 - \left(\frac{T}{T_c}\right)^2\right]$$

Table 19.5 TRANSITION TEMPERATURES AND CRITICAL FIELDS FOR SUPERCONDUCTING ELEMENTS

Element		T_c K	H_0 10^4 T	*Element*	T_c K	H_0 10^4 T
Aluminium		1.18	99	Osmium	0.61	82
Americium		1.06	—	Protactinium	< 1.0	—
Beryllium		0.026	—	Rhenium	1.70	201
Cadmium		0.52	30	Ruthenium	0.49	66
Gallium		1.08	51	Tantalum	4.47	830
Hafnium		0.128	—	Technetium	7.8	—
Indium		3.41	283	Thallium	2.38	162
Iridium		0.11	—	Thorium	1.38	—
Lanthanum	α	4.88	—	Tin	3.72	306
	β	6.0	1 600	Titanium	0.4	100
Lead		7.20	803	Tungsten	0.02	—
Mercury	α	4.15	411	Vanadium	5.4	1 310
	β	3.95	340	Zinc	0.85	53
Molybdenum		0.92	—	Zirconium	0.61	47
Niobium		9.25	1 944			

The maximum axial current which a superconducting material of cylindrical form, radius r, will sustain while remaining superconducting is given by

$$I_c = 0.5\, H_c\, r$$

Superconductivity is observed in indium and molybdenum only when these elements are very pure.[60] Traces of magnetic impurity, e.g. Fe > 0.02%, prevent its occurrence.

Table 19.6 CRITICAL TEMPERATURES OF SOME SUPERCONDUCTING ALLOYS AND COMPOUNDS

Alloy or compound	T_c K	*Ref.*	*Alloy or compound*	T_c K	*Ref.*
$Al_{10}V$	1.6	61	Nb_3Rh	2.5	63
AuGa	1.2	62	$NbSi_2$	2.9	67
AuTl	1.92	62	Nb_3Sn	18.3	63
Cr_3Os	4.03	63	Ta_3Ge	8	63
Cr_3Ru	3.43	63	$TaGe_2$	2.7	67
$EuIr_2$	2.6	64	*Ta–42%Ir	6.6	68
$HfGe_2$	2.2	65	$TaSi_2$	4.4	67
$LaGe_2$	2.65	65	Ta_3Sn	6.4	63
La_3In	10.5	64	*Tc–3%Ti	10.2–10.9	70
Mo_3Ge	1.4	63	Ti_3Ir	4.6	63
Mo_3Ir	8.1	63	Ti_3Sb	5.8	63
Mo_3Os	11.68	63	U_6Co	2.5	64
Mo_3Pt	4.56	63	U_6Fe	3.9	64
Mo_3Si	1.3	63	U_6Mn	2.3	64
Mo_2Tc_3	13.5	63	V_3Al	9.6	63
Nb_3Al	18.9	63	V_3Au	3.2	63
Nb_3Au	11	63	V_3Ga	15.4	63
Nb_3Bi	2.25	63	V_3Ge	7	63
Nb_3Ga	20.3	63	V_3In	13.9	63
Nb_5Ga_3	1.35	66	V_3Ir	1.39	63
Nb_3Ge	23	63	V_3Os	5.15	63
$NbGe_2$	16	67	V_3Pb	3.7	63
Nb_3In	8	63	V_3Re_7	9.0	64
Nb_3Ir	1.76	63	V_3Si	17.1	63
*Nb–42%Ir	4–9	68	V_3Sn	4.3	63
*Nb–40% Ir–5%O	10.4–11.7	68	$YbGe_2$	3.8	65
NbN	14.5	64	$ZrGe_2$	8	65
Nb_3P	1.83	69	Zr_2Ir	7.3	71
Nb_3Pt	10	63	$ZrIr_2$	4.1	72

*at.%

A large number of intermetallic compounds, non-stoichiometric alloys and solid solutions exhibit superconductivity. Among the compounds, the sodium chloride structure (e.g. NbN) and the A–15 or 'beta-tungsten' structure (e.g. Nb_3Sn) are two of the more common crystal types. There are currently nearly fifty A–15 compounds known to be superconducting. These alloys and compounds are potentially of considerable technological importance. Table 19.6 lists those with critical temperatures greater than 1 K.

Ternary additions can often lead to increases in critical temperature. Useful results have been discussed in references 68 and 73–77. Increased current-carrying capacity has also been seen to result from energetic particle irradiation.[78]

Superconducting compounds are usually brittle in bulk, and special techniques are required to fabricate them into useful forms. Powder metallurgical techniques may be used, while another typical method results in a composite of multifilamentary superconducting phase in a copper matrix. Superconductors may also be produced as thin films by chemical vapour deposition or sputtering (*see* references 79–83 and chapter 35).

Superconducting properties tend to be dependent upon the method of preparation and heat treatment; this observation is discussed in many of the references quoted.

For overall discussion of superconductivity, its applications, and the prospects of further developments of industrial importance, see references 64 and 84.

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20 Magnetic materials and their properties

20.1 Magnetic materials

All materials have magnetic properties. These characteristic properties may be divided into five groups: diamagnetic, paramagnetic, ferromagnetic, antiferromagnetic and ferrimagnetic. Only the ferromagnetic and ferrimagnetic materials have properties which are useful in practical applications.

Ferromagnetic properties are confined almost entirely to iron, nickel and cobalt in their alloys. The only exceptions are some alloys of manganese and some of the rare earth elements. Of these gadolinium has the highest Curie temperature, about 16°C (see the Appendix for definitions and conversion factors). Some of the magnetic properties of the ferromagnetic elements including the rare earths are given in Tables 20.1 and 20.2. Ferrimagnetism is the magnetism of the oxides of the ferromagnetic elements. These are variously called ferrites and garnets. The basic ferrite is magnetite (Fe_3O_4) which can be written as $FeO.Fe_2O_3$. By substituting for the FeO with other divalent oxides a wide range of compounds with useful properties can be produced. The main advantage of these materials is that they have high electrical resistivity which minimizes eddy currents when they are used at high frequencies.

Ferromagnetic and ferrimagnetic materials are characterized by moderate to high permeabilities (*see* Tables 20.4, 20.5 and 20.8–20.12). The permeability varies with the applied magnetic field, rising to a maximum at the knee of the B–H curve and reducing to a low value at very high fields. They also exhibit magnetic hysteresis whereby the intensity of magnetization of the material varies according to whether the applied field is being increased in a positive sense or decreased in a negative sense. A typical hysteresis loop is shown in Figure 20.1 together with some of the more important derived magnetic properties. When the magnetization is cycled continuously round a hysteresis loop, as for example when the applied field arises from an alternating current, there is an energy loss proportional to the area of the included loop. This is termed hysteresis loss, and is measured in joules per metre.[3] High hysteresis loss is associated with permanent magnetic properties exhibited by materials commonly termed 'hard' magnetic materials as these often have hard

Table 20.1 FERROMAGNETIC ELEMENTS[9]

	$J_s(T)$		*Curie temperature*		
	20°C	4 K	(°C)	σ_{4K}	$\sigma_{20°C}$
Fe	2.153	2.193	770	221.7	217.6
Ni	0.617	0.656	358	58.6	55.1
Co	1.790	1.797	1 121	162.5	161.9
Gd	0	2.47	16	250	0

Table 20.2 RARE EARTH ELEMENTS[9]

	Gd	Tb	Dy	Ho	Er	Tm
$J_s(T)$ 4 K	2.47	3.43	3.75	3.81	3.41	2.70
σ_0 4 K	250	330	350	345	300	230
T_c K	289	222	85	20	20	25

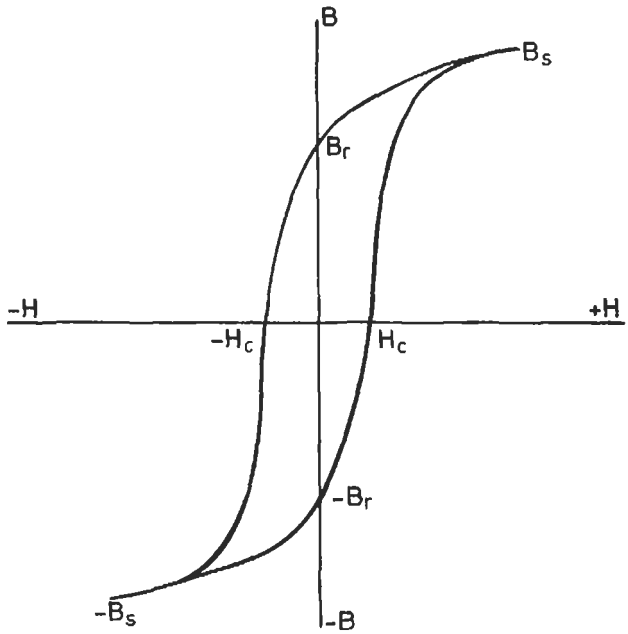


Figure 20.1 *Typical hysteresis loop*

mechanical properties. Those materials with low hysteresis loss are termed 'soft' and are difficult to magnetize permanently. The ferromagnetic properties of these elements, alloys, and compounds disappear reversibly if heated above the Curie temperature, when they become paramagnetic.

Paramagnetic substances of elongated shape tend to align themselves with an applied magnetic field as do the ferromagnetics, but do not exhibit any permanent magnetic properties when the field is removed as hysteresis is absent. Their magnetic susceptibility is very small but positive, and consequently their relative permeability is only slightly greater than unity. The susceptibility is generally independent of field strength but may decrease with increasing temperature. Among the paramagnetic substances are included many iron salts and rare-earth elements salts, palladium and platinum, sodium, potassium, and oxygen, and the ferromagnetics above their Curie point.

The diamagnetic substances take on a very small magnetization which is opposed to the sense of the applied field. Thus an elongated specimen will align itself transversely to a non-uniform field. The diamagnetics have negative susceptibilities and consequently permeabilities which are very slightly less than unity. Many of the metals and most non-metals are diamagnetic. It is usual to compare paramagnetic and diamagnetic substances by their susceptibilities rather than by permeability or saturation magnetization as for the ferromagnetic materials. The mass susceptibilities of the elements at room temperature are given in Table 20.3[5–9]

For bulk applications of magnetic material iron, steel or cast iron are used. They have the advantage of cheapness and strength. These materials should only be used for d.c. applications as they have low electrical resistivity which would give rise to eddy currents if used in alternating fields. The properties of some steels and cast irons are given in Tables 20.4 and 20.5.[10–13]

20.2 Permanent magnet materials[14,15]

The properties of a permanent magnet material are given by the demagnetization curve, Figure 20.2, the second quadrant of the *B–H* hysteresis loop. This extends from the remanence B_r to the coercivity H_{cB}. It can be shown that when a piece of permanent magnet material is put into a magnetic circuit, the magnetic field generated in a gap in the circuit is proportional to BHV, where

Table 20.3 MASS SUSCEPTIBILITIES OF THE ELEMENTS[5–9]

Element	*Atomic No.*	*Mass susceptibility* $10^{-8}\,m^3\,kg^{-1}$	*Element*	*Atomic No.*	*Mass susceptibility* $10^{-8}\,m^3\,kg^{-1}$
H	1	−2.48	Ag	47	−0.23
He	2	−0.59	Cd	48	−0.23
			In	49	−0.14
Li	3	+0.63	Sn	50	−0.31
Be	4	−1.26	Sb	51	−1.09
B	5	−0.87	Te	52	−0.39
C	6	−0.62	L	53	−0.45
N	7	−1.00	Xc	54	−0.43
O	8	+133.5			
F	9		Cs	55	−0.28
Ne	10	−0.41	Ba	56	+1.13
			La	57	+1.02
Na	11	+0.64	Ce	58	+22.0
Mg	12	+0.69	Pr	59	+42.3
Al	13	+0.82	Nd	60	+48.0
Si	14	−0.16	Pm	61	—
P	15	−1.13	Sm	62	+11.1
S	16	−0.62	Eu	63	+27.6
Cl	17	−0.72?	Gd	64	*
Ar	18	−0.60	Tb	65	+1 360
			Dy	66	+545
K	19	+0.65	Ho	67	+549
Ca	20	+1.38	Er	68	+377
Sc	21	+8.80	Tm	69	+199
Ti	22	+4.21	Yb	70	+0.59
V	23	+6.28			
Cr	24	+4.45	Lu	71	+0.12
Mn	25	+12.2	Hf	72	+0.53
Fe	26	*	Ta	73	+1.07
Co	27	*	W	74	+0.39
Ni	28	*	Re	75	+0.46
			Os	76	+0.06
Cu	29	−0.10	Ir	77	+0.23
Zn	30	−0.20	Pt	78	+1.22
Ga	31	−0.30			
Ge	32	−0.15	Au	79	−0.18
As	33	−0.39	Hg	80	−0.21
Se	34	−0.40	Tl	81	−0.30
Br	35	−0.49	Pb	82	−0.15
Kr	36	−0.44	Bi	83	−1.70
			Po	84	—
Rb	37	+0.26	At	85	—
Sr	38	−0.25	Rn	86	—
Y	39	+6.66			
Zr	40	+1.66	Fr	87	—
Nb	41	+2.81	Ra	88	—
			Ac	89	—
Mo	42	+1.17	Th	90	+0.53
Tc	43	+3.42	Pa	91	+3.25
Ru	44	+0.54	U	92	+2·15
Rh	45	+1.32	Np	93	—
Pd	46	+6.57	Pu	94	+3.14
			Am	95	+5.15

B and H are the corresponding points at a point on the demagnetization curve and V is the volume of permanent magnet. So to obtain a given field with the minimum volume of magnet material we require the product BH to be a maximum. The magnet is then designed so that its B, H value is as close as possible to the $(BH)_{max}$ value. It is also useful to use the BH_{max} value to compare the characteristics of materials. Generally the material with the highest $(BH)_{max}$ will be chosen but this has to be weighed against such considerations as cost, shape, manufacturing problems and stability.

Table 20.4 MAGNETIC PROPERTIES OF WROUGHT STEELS[12-13]

*Grade**	*En No*	*Material*	*Flux density* T		*Rel. permeability*		*Max. flux density* T	*Remanence* T	*Coercive force* $A\,m^{-1}$
			$H = 4\,kA\,m^{-1}$	$H = 8\,kA\,m^{-1}$	Maximum at	$H\,a\,m^{-1}$	$H = 20\,kA\,m^{-1}$		
220M07	1A	Free cutting carbon steel C 0.15 max., Si 0.40 max., Mn 0.90–1.30, S 0.20–0.35	1.50	1.76	1 200	800	1.95	0.87	240–400
040A04	2A/1	Low carbon steel C 0.08 max., Si 0.40 max., Mn 0.50 max., S and P 0.05 max.	1.67	1.77	2 400–5 000	400–160	1.96	0.5–1.1	40–120
070M20	3	Carbon steel C 0.25 max., Si 0.05–0.35, Mn 1.00 max., S and P 0.05 max.	1.57	1.74	1 100	800	1.96	1.00	240–400
080M30	5	'30' carbon C 0.25–0.35, Si 0.05–0.35, Mn 0.60–1.00, S and P 0.05 max.	1.52	1.73	1 000	800	1.88	—	800
070M55	9	'55' carbon C 0.50–0.60, Si 0.10–0.40, Mn 0.50–0.90, S and P 0.05 max.	1.45	1.67	400	2 000	1.81	1.30	1 200
Low alloy steels		C 0.20–0.60, Si 0.1–0.40, Mn 2.0 max., S and P 0.05 max., Ni 1.0 max., Cr 1.0 max.	1.40–1.65	1.70–1.90	400–650	—	1.75–1.90	0.88–1.55	600–1 600
3% Nickel steel		C 0.20–0.60, Si 0.10–0.40, Mn 0.8 max., S and P 0.05 max., Ni 2.5–3.0, Cr 1.0 max., Mo 0.5 max.	1.50–1.70	1.73–1.85	600	1 600	1.85–1.95	1.43	980
3% Chromium steel		C 0.20–0.60, Si 0.10–0.40, Mn 0.8 max., S and P 0.05 max., Cr 3.0, Ni 0.40 max.	1.65	1.75	680	1 600	1.75–1.85	1.50	880
Chromium rust resisting steels		C 0.35 max., Si 0.1 max., Mn 1.0 max., S and P 0.05 max., Ni 3.0 max., Cr 12–20	0.95–1.30	1.06–1.40	660	720	1.43–1.64	0.60–1.00	400–1 250

Information from 'The Mechanical and Physical Properties of British Standard En Steels' by J. Woolman and R. A. Mottram, volumes 1, 2 and 3, Pergamon, Oxford, 1964.[12]

*The numbered grades refer to BS 970:PART 1:1983 (*see* Ref. 13).

Table 20.5 SOME DATA ON THE MAGNETIC PROPERTIES OF CAST STEELS AND CAST IRONS

Material	*Condition*	*Flux density* T		*Rel. permeability*		*Max. flux density* T	*Remanence* T	*Coercive force* A m^{-1}
		$H=$ 4 kA m^{-1}	$H=$ 8 kA m^{-1}	Maximum at H A m^{-1}		$H=$ 20 kA m^{-1}	$H=$ 20 kA m^{-1}	$H=$ 20 kA m^{-1}
Cast steel[11]								
0.10% carbon steel, Si, 0.33%; Mn, 0.67%	Annealed	1.62	1.74	2420	216	1.92	0.80	136
	Normalized	1.64	1.76	1950	248	1.96	0.85	168
	As-cast	1.61	1.74	2100	208	1.95	0.66	128
0.19% carbon steel, Si, 0.30%; Mn, 0.48%	Annealed	1.60	1.73	2100	224	188	0.87	156
	Normalized	1.57	1.72	1520	360	1.91	0.90	216
	As-cast	1.55	1.69	1720	232	1.89	0.73	168
0.34% carbon steel, Si, 0.44%, Mn, 0.55%	Annealed	1.53	1.66	1200	400	1.85	1.05	296
	Normalized	1.50	1.67	970	575	187	1.05	440
	As-cast	1.45	1.65	840	480	1.87	0.85	440
Manganese steel 0.19% C, 0.48% Si, 1.14% Mn	A 925°C	1.51	1.66	1300	400	1.86	—	—
0.29% C, 0.29% Si, 1.40% Mn	A 950°C, N 880°C, T 600°C, a.c.	1.50	1.68	650	960	1.78	—	—
0.31% C, 0.52% Si, 1.37% Mn	A 950°C, OQ 860°C, T°629°C, a.c.	1.55	1.65	750	960	1.70	—	—
Chromium-molybdenum steel 0.31% C, 0.69% Mn	A 925°C, N 880°C, T 700°C, a.c.	1.45	1.59	—	—	1.76	—	—
1.16% Cr, 0.39% Mo	A 925°C, OQ 860°C, T 650°C, a.c.	1.54	1.66	—	—	1.81	—	—
						Hysteresis loss J M^{-3} cycle^{-1}		
Cast-irons[10]								
Grey iron T.C. 3.12%, Si 2.2%, Mn 0.67%, P 0.13% (low phosphorus)	As-cast	0.70	0.86	315	640	2700	0.41	560
	Annealed	0.93	1.07	1560	200	700	0.44	200
Grey iron T.C. 3.3%, Si 2.04%, Mn 0.52%, P 1.03% (high phosphorus)	As-cast	0.79	0.97	281	1040	2730	0.43	720
	Annealed	0.85	1.00	760	320	1190	0.44	280
Whiteheart Malleable TC 1.01%, Si 0.66%, Mn 0.25%	Pearlitic centre	1.32	1.42	730	560	1490	0.75	360
TC 0.46%, Si 0.66%, Mn 0.25%	Mainly ferritic	1.35	1.61	1455	280	840	0.74	200
Blackheart Malleable TC 1.26%, Si 0.83%, Mn 0.26%		1.40	—	2120	176	490	0.62	120
Spheroidal Graphite TC 2.9%, Si 2.61%, Mn 0.72%, Ni 2.18%	Pearlitic	0.93	1.12	290	1200	3040	0.54	920
	Annealed, ferritic	1.14	1.26	1150	320	700	0.46	200
Spheroidal Graphite TC 3.64%, Si 1.41%, Mn 0.3% (nickel free)	Annealed	1.23	1.42	2060	240	450	0.61	120

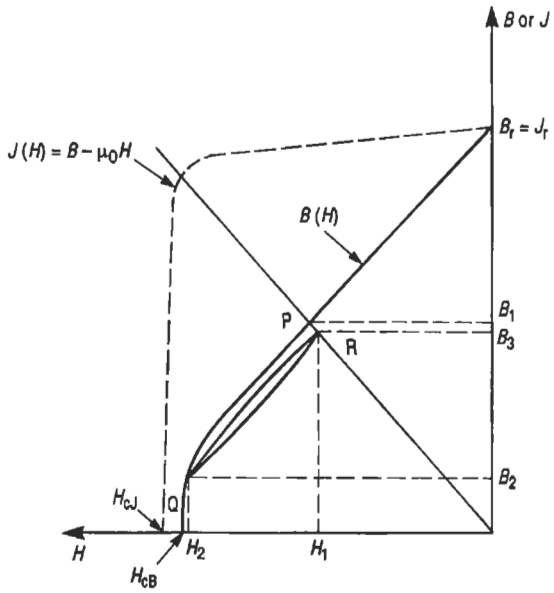


Figure 20.2 *Demagnetization curve and recoil loop*

When the magnet is fully magnetized in a completed magnetic circuit, the working point is the remanence B_r. When a gap is made in the circuit, the magnet will be partly demagnetized and its working point will fall to, say, the point P. If now a further demagnetizing field is applied to the magnet corresponding to $H_1 - H_2$ the flux density will be reduced to B_2. If this extra field $H_1 - H_2$ is removed the field will recoil along the narrow loop QR to the point R. The corresponding flux density is B_3. This narrow loop is called the recoil loop and its slope is $\mu = \mu_0 \mu_r$ where μ_r is the relative recoil permeability and μ_0 is the magnetic constant ($=4\pi \times 10^{-7}$). This is an important consideration in dynamic applications such as motors, generators and lifting devices where the working point of the magnet changes as the magnetic circuit configuration changes. It is also important when considering premagnetizing before assembly into a magnetic circuit. If μ_r is nearly equal to unity as it is for ferrites and for rare earth alloys then the magnets can be premagnetized before assembly into a magnetic circuit without much loss of available flux. However, if μ_r is considerably greater than unity, care must be taken to magnetize the magnet in the assembled magnetic circuit.

The dotted curve in Figure 20.2 is the J–H curve where $B = \mu_0 H + J$. For materials with B_r much greater than $\mu_0 H_{cB}$, e.g. Alnico, the two curves are almost identical, but for ferries and rare earth alloys where B_r and $\mu_0 H_{cB}$ are close in value the curves become quite different. The J–H curve has only a very gradual slope from B_r; this indicates that the magnetization in the material is nearly uniform and a new parameters H_{cJ} is introduced. This intrinsic coercivity H_{cJ} is a measure of the difficulty or ease of demagnetization. As the value of H_{cJ} is increased the more the material will resist demagnetization due to stray fields, etc. However, as a field of at least three times H_{cJ} must be applied to the magnet for magnetization, difficulties may be encountered in attaining the full magnetization if H_{cJ} is too high.

Magnets in the three main groups Alnico, ferrites and rare earth alloys are generally made anisotropic with the properties in one direction considerably better than in the other directions. This best direction is called the preferred direction of magnetization. The curves and parameters supplied for such a material refer to the properties in this preferred direction.

To choose between these three materials for a particular application, Alnico must be used where magnetic stability is a requirement and this would apply in any type of instrument application. Ferrite will be used where cost is the main consideration and rare earth magnets will be used if the highest possible strength is required or if miniaturization is needed.

20.2.1 Alnico alloys

A wide range of alloys with magnetically useful properties is based on the Al–Ni–Co–Fe system. They are characterized by high remanence, available energy and moderately high coercivity. They are very stable against vibration and have the widest useful temperature range (up to over 500°C) of any permanent magnet material. But they are mechanically hard, impossible to forge, and difficult to machine except by grinding and special methods such as spark erosion.

The preferred form of magnet is a relatively simple shape made by casting or sintering, precision ground on essential surfaces only. Soft-iron pole pieces may be clamped on or held by a suitable adhesive such as Araldite. Soldering, diecasting and even brazing (with precautions against overheating) may be used.

The commonest alloys contain 23–25% cobalt, 12–14% nickel, about 8% aluminium, a few per cent copper and sometimes small additions of niobium and silicon, with the balance iron. They are cooled at a controlled rate in a magnetic field applied in the direction in which the magnets are to be magnetized. The properties are much improved in this direction at the expense of those in other directions. There is finally a fairly prolonged and sometimes rather complicated treatment at temperatures in the range 650–550°C.

The field cooling is much more effective in producing anisotropic properties if the magnets are cast with a columnar structure. Basically a columnar structure is produced by casting the alloy into a hot mould with a cold chill. The mould may be made of special materials which can be preheated to at least 1 250°C in a furnace, or alternatively contain chemicals which heat it by an exothermic reaction. Either method is inconvenient and expensive; there are also limitations on the lengths and shapes of magnets that can be made columnar. This Columax is therefore regarded as a rather expensive, quality material.

The coercivity of Alnico can be improved by a factor of two to three by increasing the cobalt content to 30–40% and adding 5–8% of titanium with possibly some niobium. For the best properties it is necessary to hold these alloys for several minutes in a magnetic field at a constant temperature, accurately controlled to $\pm 10^{\circ}$C, instead of the usual field cooling process. This heat treatment as well as the high cobalt content makes these alloys expensive and they are only used where the higher coercivity is required. Columnar versions of these alloys can also be made but these are only used for very specialized applications.

The Alnico alloys can be produced as castings of up to 100 kg and down to a few grams in weight but it is found more economical to produce the smaller sizes of 50 g and less by the sintering process. In all cases it is advisable to contact the manufacturers before any design is considered.

20.2.2 Ferrite

The permanent magnet ferrites (also called ceramics) are mixed oxides of iron (ferric) oxide with a divalent heavy metal oxide, usually either barium or strontium. These ferrites have a hexagonal crystal structure, the very high anistropy of which gives rise to high values of coercivity, e.g. 150–300 kA m^{-1} (compared with about 110 kA m^{-1} for the best Alnico alloys). The general formula is $MO.5.9Fe_2O_3$ where M is either barium or strontium, and the crystal structure is called magneto plumbite as it was originally found in the equivalent lead oxide compound. These ferrites are made by mixing together barium or strontium carbonate with iron oxide in the correct proportions. The mixture is fired in a mildly oxidizing atmosphere and the resulting mixture is milled to a particle size of about 1 micron. This powder is then pressed in a die to the required shape (with a shrinkage allowance), and anisotropic magnets are produced by applying a magnetic field in the direction of pressing. After pressing, the compact is fired. This material is a ceramic and can only be cut by high speed slitting wheels. Ferrite magnets are produced in large quantities in a variety of sizes for different applications. Flat rings are made for loudspeakers ranging up to 300 mm in diameter with a thickness of up to 25 mm. Segments are made for motors with ruling diameters from 40 to 160 mm and rectangular blocks are made for separators with dimensions of up to 150 × 100 × 25 mm. These blocks can be built up into assemblies or cut down into smaller pieces for a variety of applications. In each of these cases the preferred direction of magnetization is through the shortest dimension. generally the magnetic length does not exceed 25 mm and if a longer length is required this is built up with magnets in series.

The great success of permanent magnet ferrites is due to the low price per unit of available magnetic energy, the high coercivities, the high restivities and the low density. The isotropic grades are the least expensive to manufacture and may be magnetized into complex pole configurations;

they are used for a wide range of relatively small-scale applications. The largest application in terms of market volume is for magnets for loudspeakers; here the high-remanence anisotropic grades are used. The other high-volume application is for field magnets in small d.c. motors, particularly those used in the automotive industry, e.g. for windscreen wipers, blowers, etc. In this application the high-coercivity anisotropic ferrite is formed into an arc-shaped segment, magnetized radially; a pair of segments embrace the armature and provide the stator field. Other applications of anisotropic hard ferrites include magnetic chucks and magnetic filters and separators.

20.2.3 Rare earth cobalt alloys

These are the results of a fairly recent development and the first commercial material was $SmCo_5$. The alloy powder is produced either by reducing the rare earth powder together with cobalt powder or by preparing the alloy and powdering it down. The powder is compacted and pressed, almost invariably in a magnetic field, to produce an anisotropic compact. This is then sintered at $1\,155 \pm 15$°C and followed by a tempering treatment at about 900°C. It must be emphasized that during all the processing of these rare earth alloys a protective atmosphere is used to prevent the oxidation of the rare earth metals which are very reactive.

Another development in this series is the Sm_2Co_{17} composition which is really the generic name for a whole series of binary and multi-phase alloys with other transition elements replacing cobalt. These other elements include copper, chromium, manganese, zirconium and iron. The ratio of transition elements to rare earth may be less than the 8.5 given by the composition. An anisotropic compact is produced and sintered at 1 150 to 1 250°C, and this is followed by a solution treatment at 1 100 to 1 250°C. The compact is then step aged at temperatures from 900°C down to 400°C over a period of at least 20 h. This complicated heat treatment and difficulties with powder production have made the magnets rather difficult to produce with consistent properties. It is however the most stable of the rare earth alloys and has a higher remanence and $(BH)_{max}$ than the $SmCo_5$ alloy.

In both of these alloy systems the properties are due to a very strong magnetocrystalline anisotropy related to the hexagonal crystal structure. The range of sizes which can normally be produced is from about 1 mm cubes up to blocks of $50 \times 50 \times 25$ mm, the short dimension being the preferred direction. These magnets are very brittle and must be handled with care to prevent chipping or cracking. They can only be machined by grinding or slitting, and they cannot be drilled or turned. The magnets may be magnetized prior to assembly without flux loss because they combine a relative recoil permeability close to unity with a high coercivity. However, because of the handling problems with these brittle magnets it is often more convenient for the user to magnetize during assembly.

20.2.4 Neodymium iron boron

This alloy was announced in 1983 and it has generated a great deal of interest because at room temperature it has better properties than any previously known alloy. It is also a cobalt-free alloy and uses neodymium which is more abundant than samarium. These two factors make the raw material costs quite considerably less than those of the samarium cobalt alloys.

There are two main routes for the production of magnets from these alloys. The first is the conventional route similar to that used for $SmCo_5$. The constituents of the alloy are melted together, and the material is then powdered, pressed in a magnetic field and sintered. The basic alloy with this route is the atomic composition $Nd_{15}B_8Fe_{77}$. The second method is to use the melt spinning process where the molten alloy is ejected under pressure on to a water cooled wheel which is rotating at high speed. This cools the alloy very rapidly and an amorphous glass-like tape is produced. This tape is annealed at 650°C, which recrystallizes the alloy, and then it is mechanically broken into flake. The basic atomic composition of the alloy for this process is 13.5% Nd 4.75% B 81.75% Fe. There are advantages in each of these methods. To get the best properties the conventional sintering route must be used but the production of the powder is rather slow and expensive. Melt spinning allows the powder to be produced more easily and cheaply. This method is ideal for the production of flake for use in the manufacture of isotropic bonded material, this product being called Magnequench I. The production of anisotropic material from the flake is more difficult and expensive.

The mechanism which provides the high value of the coercivity is crystal anisotropy, in the tetragonal crystals of the alloy. The particle size required for optimum properties is about 3 μm. Powdering can be achieved by ball milling; however the hydrogen decrepitation process has been applied very successfully. This process, which involves the absorption of large volumes of hydrogen

by the alloy followed by desorption, produces much less damage to the particles, resulting in better properties.

There are two disadvantages of these neodymium alloys when compared to the rare earth cobalt alloys. They suffer from corrosion and rusting, although this can be prevented by the use of a suitable coating. They also have a relatively low Curie temperature of 330°C resulting in instability with a rapid decrease in flux with increasing temperature. The stability can be improved by additions of dysprosium, niobium and/or vanadium, making the alloy useful up to 150°C. Similar comments to those for the rare earth cobalt alloys apply here regarding sizes, machining and magnetizing but these neodymium alloys are much less brittle.

These alloys are being used in a wide range of rotating machine applications for both a.c. and d.c. generators and motors including stepper motors. They are also used for holding and lifting devices and for motors for compact discs. More specialized applications include body scanners using magnetic resonance imaging (MRI) and particle beam focusing devices.

20.2.5 Bonded materials

Each of the above materials can in the powdered form be mixed with a bond. These bonds can be rubbers, polymers or plastics, and they may be flexible or rigid. The flexible rubber bonded ferrites have found wide application in holding and display services and the best quality anisotropic material is used in small motors. Alnico and rare earth cobalt are also made in bonded forms and they have the advantages of a uniform level of properties and freedom from cracking. Their magnetic properties are not so good as the unbonded materials: at best the BH_{max} is about 50% lower.

20.2.6 Other materials

There are a number of other permanent magnet materials with minor applications. These materials make up less than 1% of the total production. They mainly find applications because they can be mechanically formed into shape, which is not possible for Alnico, ferrites or rare earth alloys. It must be emphasized that these other materials are only available in a limited range of sizes and shapes. Steels which were the original permanent magnets are now almost obsolete because their properties are inferior to those of the materials mentioned above. They do, however, find applications in hysteresis motors where intermediate coercivities are required. Cunife (Cu Ni Fe) and Cr Fe Co are alloys which can be rolled and drawn into wire and the anisotropy is produced by this rolling or drawing. Cr Fe Co produced by rolling can have properties similar to those of anisotropic Alnico. Platinum cobalt (Pt Co), which has a very high coercivity, was much used in the early days of space research. For most applications it has now been replaced by rare earth alloys. However, it is still used for medical and other applications where the resistance to corrosion is required. Other materials which were used in the past are Lodex, which consisted of fine electrolysed particles of iron cobalt, Vicalloy (V Co Fe) and Mn Al C alloys. These materials are now obsolete because of cost, lack of demand and production difficulties.

20.2.7 Properties, names and applications

The range of properties for each class of material is given in Table 20.6. These ranges include deliberate variations in properties obtained by small changes in composition and heat treatment. These are listed by manufacturers with different names, numbers or letters such as Feroba 3, 4 or Ferroxdure 300, 380.

The most common applications of each broad class of material and popular trade names are given in Table 20.7.[14–15]

20.3 Magnetically soft materials

Materials or alloys which are classed as magnetically soft, and generally with a relatively high permeability, are used for a wide range of applications including transformer laminations, armature

Table 20.6 CHARACTERISTICS OF PERMANENT-MAGNET MATERIALS

B_r Remanence, T
$(BH)_{max}$ Energy product, kJ m^{-3}
H_{cB} Coercivity, kA/m^{-1}
μ_r Relative recoil permeability

Material	B_r	$(BH)_{max}$	H_{cB}	μ_r
Alnico				
Normal anisotropic	1.1–1.3	36–43	46–60	2.6–4.4
High coercivity	0.8–0.9	32–46	95–150	2.0–2.8
Columnar	1.35	60	60	1.8
Ferrites (ceramics)				
Barium isotropic[a]	0.22	8	130–155	1.2
anisotropic[a]	0.39	28.5	150	1.05
Strontium anisotropic[a]	0.36–0.43	24–34	240–300	1.05
Bonded ferrite				
Isotropic[a]	0.14	3.2	90	1.1
Anisotropic[a]	0.23–0.27	10–14	180	1.05
Rare earth				
$SmCo_5$ sintered[b]	0.9	160	640–700	1.05
$SmCo_5$ bonded[b]	0.5–0.6	56–64	400–460	1.1
Sm_2Co_{17} sintered[c]	1.1	150–240	500–900	1.05
NdFeB[d]	1.0–1.2	200–275	700–835	1.05
Others				
Cunife	0.54	10	40	—
CrFeCo	1.3	40–46	46	3–4
PtCo	0.62	72	370	1.1

Intrinsic coercivity H_{cT}(kA m^{-1}) [a] 160–3.10; [b] 800–1.500; [c] 600–1 300; [d] 750–1 900.
The Curie temperature of Alnico is 800–8.50°C, of ferrite 450°C, of SmCo over 700°C and for NdFeB it is 300°C. The Alnicos have a resistivity of about $50 \times 10^{-8}\,\Omega$m, for the ferrites it is about $10^{4}\,\Omega$m and for the rare earths $90–140 \times 10^{-3}\,\Omega$m.

Table 20.7 NAMES AND APPLICATIONS OF PERMANENT MAGNET MATERIALS

Material		*Names*	*Applications*
Alnico		Alcomax 3 Alnico 5	Moving coil instruments, watt-hour meters, loudspeakers (TV), telephone receivers, weighing machines, relays.
		Hycomax 3 Alnico 8	Centre core instruments, magnetic bearings, thermostats and relays.
		Columax Alnico 5–7	Nuclear magnetic resonance, large motors, loudspeakers (TV).
Ferrite Anisotropic	(Sr)	Ferroxdure 380 Feroba 3 Ceramic 7	D.c. motors and starter motors, holding devices and chucks, mineral separators.
	(Ba)	Ferroxdure 300 Feroba 2 Ceramic 5	Loudspeakers (HiFi), holding devices and chucks, mineral separators.
Rare earth cobalt	($SmCo_5$)	Supermagloy 52 Res 190	Stepper and servo motors, travelling wave tubes, centrifuges, klystrons and gyroscopes.
	(Sm_2Co_{17})	Supermagloy 53	Servomotors, couplings, clutches and frictionless bearings.
Neodymium iron boron (sintered)		Neodure 270 Neorem 30	Computer applications including track shifters and compact disc motors, MRI body scanners, mineral separators.
	(bonded)		Walkman equipment, small motors including hand tools.

stampings and cores in electrical machinery. They also include materials of considerable importance in the electronic and communication industries. Many special materials of widely different chemical compositions have been developed to meet specialized requirements. These are not confined to metallic alloys and ceramic oxides have become increasingly important.

Sometimes several conflicting attributes are required in magnetically soft materials for a given application. It is for this reason that a range of materials from iron through to silicon steels, high nickel–iron alloys and ferrites have emerged. Usually, the most important requirement is that the hysteresis loss due to cyclic magnetization should be as low as possible. The eddy current loss, which is due to the induction of electric currents in the material by the changing magnetic flux, should also be small. Generally the magnetic permeability should be as high as possible, particularly the maximum permeability, and in certain special cases the initial permeability also. Sometimes the requirement is for a high permeability at low field strengths. In general, the saturation intensity should be as high as other conditions will permit. For magnetic temperature compensation there should be a linear relation, over a known range of temperature, between permeability and temperature.

Relevant data concerning a wide selection of materials are given in Tables 20.8 to 20.12 and are discussed in the corresponding sections.

20.3.1 Silicon–iron alloys

For the magnetic circuits of the larger pieces of electrical equipment normally operated at power frequencies of 50 Hz, such as power transformers, alternators and electric motors of all sizes, a magnetic material is essential which will have a low hysteresis, high resistivity and a high value of magnetic saturation. Its production in the form of thin sheet or strip must also be possible, and in view of the big tonnages essential for such purposes it must not be expensive. Silicon–iron alloys are the only ones which meet all these conflicting requirements.

Over the years, the quality of silicon steels has been continuously improved and more has been learned about the effects of silicon on the magnetic properties. these effects are briefly as follows:

1. Silicon precipitates the major portion of the oxygen dissolved in the steel, which reduces hysteresis loss and magnetic ageing.
2. Silicon increases the electrical resistivity and thus reduces the eddy current loss, which is proportional to the resistivity (*see* Figure 20.3).

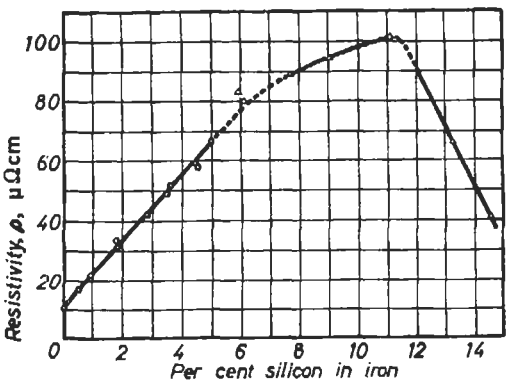


Figure 20.3 *Electrical resistivities of iron-rich iron–silicon alloys.*

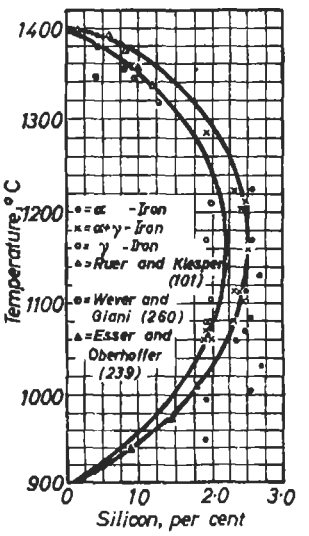


Figure 20.4 *The gamma phase region*

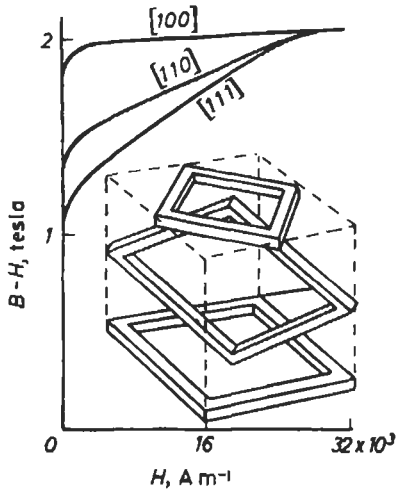


Figure 20.5 *Magnetization curves for 3.85% silicon-iron single crystals at high field strengths in three directions*

3. With over 2.5% silicon the alloys are outside the gamma loop on the equilibrium diagram, i.e. the alpha–gamma change point is suppressed (*see* Figure 20.4). Alloys of more than 2.5% silicon can therefore be annealed at high temperatures without recrystallization occurring on cooling. As a result it is easier to produce large grain size in the finished sheet, with a corresponding reduction in hysteresis loss.
4. Silicon precipitates the carbon as graphite if it exceeds about 0.05%. Carbon present as graphite has no effect on hysteresis loss.

It is possible to orient the grains in silicon steels by cold rolling and heat treatments. Improvements in this grain-oriented sheet have been made as follows:

1. Limitation of the silicon content to about 3%. Above this value it is difficult to produce good quality sheet because of mechanical difficulties.
2. Reduction in the sheet thickness. The minimum thickness is 0.23 mm, which is limited by grain growth considerations.
3. Reductions of impurities to the minimum economic value. Impurities which increase hysteresis are those which occupy interstitial positions in the crystal lattice, e.g. carbon, oxygen, nitrogen and sulphur.
4. Improvements in the control of annealing equipment and protective atmospheres during final annealing.

The grain-oriented steel strip is used for transformers. The grain orientation is parallel to the rolling direction and in the transformer the flux is arranged so that it is parallel to this direction. This gives the advantage that the permeability is better and the hysteresis is lower with the direction of magnetization parallel to the cube edge of the crystal lattice (*see* Figure 20.5).

During the annealing process a glass film is produced on the steel surface and this film gives a longitudinal tension in the sheet and provides insulation. This tension improves the magnetic properties of the steel, including a reduction in the magnetostriction which reduces the acoustic noise of the transformer. A phosphate coating is applied to complete the tensioning and insulation. The grain size of these sheets is comparatively large and the resulting domain boundaries are quite widely spaced. Artificial grain boundaries can be produced by laying down lines of ablated spots on the steel surface to give a stress and atomic disruption pattern which pins domain walls and leads to a smaller wall spacing. Various methods have been used to produce this ablating including spark and laser techniques.

In addition to the grain oriented material there is a need in rotating machinary applications for sheets which are comparatively isotropic and less expensive. The silicon content is generally lower as the minimum core loss is less important than the high-saturation magnetization needed for maximum torque.

Manufacturers offer a series of alloys whose properties are given in Table 20.8. These alloys conform to the British Standards and their international equivalents given in ref. 22. Methods of test are also given in these standards. In the past the Epstein square has been used by there is a rapidly growing trend towards the use of single-sheet testers which greatly reduce the labour involved.

Table 20.8 TYPICAL PROPERTIES OF SILICON STEELS[16]

Grade identity	*Thickness* mm	*Typical specific total loss at* $B = 1.5$T; 50 Hz (*or* 1.7T; 50 Hz where stated) (W kg)	*Typical specific apparent power at* $B = 1.5$T; 50 Hz (*or* 1.7T; 50 Hz *where stated*) (VA kg^{-1})	*Nominal silicon content* %	*Resistivity* $\Omega m \times 10^8$	*Stacking factor* %	$\hat{B}$ *at* $H = 5000$ A m^{-1} (*or* 1000 A m^{-1} *where stated*) T	*Typical applications*
Grain oriented: magnetic properties measured in direction of rolling only								
Unisil								
27MOH	0.27	1.03 (1.7; 50)	1.4 (1.7; 50)	2.9	45	96	1.94 (1000)	High-efficiency power transformers
30M2H	0.30	1.12 (1.7; 50)	1.55 (1.7; 50)	2.9	45	96.5	1.92 (1000)	
Unisil								
23M3	0.23	0.75	1.00	3.1	48	96	1.85 (1000)	
27M4	0.27	0.84	1.16	3.1	48	96	1.85 (1000)	
30M5	0.30	0.89	1.32	3.1	48	96.5	1.85 (1000)	
35M6	0.35	1.00	1.39	3.1	48	97	1.84 (1000)	
Non-oriented: magnetic properties measured on a sample comprising equal number of strips taken at 0° and at 90° to the direction of rolling								
Transil 300-35-A5	0.35	2.95	30	2.9	48	98	1.65	Large rotating machines
Losil 400-50-A5	0.50	3.60	19	2.4	44	98	1.69	Small transformers/chokes
Losil 800-65-A5	0.65	6.50	14	1.3	29	98	1.75	Motors and FHP motors
Non-oriented: grades supplied in the 'semi-processed' condition and which require a decarburizing anneal after cutting/punching to attain full magnetic properties								
Newcor 800-65-D5	0.65	7.00	10	Nil	12	97	1.77	Motors and FHP motors
Newcor 1000-65-D5	0.65	8.80	11.5	Nil	12	97	1.74	
Tensile grades								
Tensiloy 250	1.60	—	—	Nil	—	—	1.60	Pole pieces large rotating machines

Available from British Steel, Newport, Gwent, UK.

Table 20.9 TYPICAL PROPERTIES OF SOME MAGNETICALLY SOFT FERRITES*,[18–20]

	Conditions		*Ferrite grade*					
Parameter	f (kHz)	$\hat{B}$ (mT)	(i)	(ii)	(iii)	(iv)	(v)	*Units*
Approximate composition:								
$MnO/ZnO/Fe_2O_3$			27/20/53	25/22/53	30/20/49	34/14/52	—	mol %
$NiO/ZnO/Fe_2O_3$			—	—	—	—	32/18/50	mol %
Initial permeability, μ_i	< 10	< 0.1	1 200–2 500	3 800–10 000	350–500	1 000–3 000	70–150	
Temperature factor, $\Delta\mu_i/\mu^2\Delta\theta$	< 10	< 0.1	0.5–1.5	—	20	—	0–8	$°C^{-1} \times 10^{-6}$
(5 to 55°C)	30		0.8–2.0	5–10	—	—	—	
Residual loss factor (tan δ_r)/μ_i	100	< 0.1	1.5–3.0	10–50	30	—	—	10^{-6}
	10^3		—	—	75	—	20–40	
	10×10^3		—	—	—	—	60–100	
Hysteresis coefficient, η	10	1 to 3	0.5–1.0	0.1–1.0	—	—	2–10	$mT^{-1} \times 10^{-6}$
Saturation flux density, B_{sat} (at 1 kA/m)			0.35–0.45	0.35–0.45	0.23–0.27	0.4–0.5	0.3–0.4	T
Curie point, θ_c	< 10	< 0.1	130–250	90–220	130–160	180–280	250–400	°C
Resistivity	d.c.		1–5	0.05–0.5	1–5	1–5	$> 10^3$	Ω m
Applications			Quality inductors	Wide-band or pulse transformers	Deflection yokes	High-power transformers	Quality inductors 2–12 MHz	

* At 25°C unless otherwise stated.

20.3.2 Ferrites[18–20] and garnets[20]

Ferrites are iron oxide compounds usually containing at least one other metallic ion. The magnetic iron oxides Fe_3O_4 and Fe_2O_3, both of which are used in magnetic recording, are also included with the ferrites. The most important of the many ferrite materials now known are sintered ceramics of high resistivity, together with saturation magnetizations up to 0.5 T at room teperature. One structural class is the barium hexaferrites with high coercivities used as permanent magnets. The other two structural classes are the spinels and the garnets.

The spinel-structured ferrites are mixed oxides with the general composition $MO.Fe_2O_3$ where M may be Fe, Ni, Mn, Zn, Co, Cu, Li or Al or mixtures of these. They are prepared from the constituent oxides which have been milled to a fine powder, preferably of the same particle size and intimately mixed. This mixture is calcined at about 1 000°C followed by crushing and milling and pressing the powder in a die or extrusion to the required shape. The resulting compact is a black brittle ceramic and any subsequent machining must be by grinding. They may be prepared with high permeability, and by virtue of the high resistivity, which renders eddy current levels negligible, can be used at frequencies up to 10 or 20 MHz as the solid core of inductors or transformers. The losses which do occur are a combination of hysteresis, eddy current, and residual losses which may be separately controlled by composition and processing conditions with due regard to the permeability required and frequency of operation.

The saturation flux density of ferrites is low, making them unsuitable for use in power or high flux transformers. Their use is therefore almost entirely in the electronic and telecommunications industry where they are now largely replacing laminated alloy and powder cores.

Typical properties of the commonly employed manganese–zinc and nickel–zinc ferrites are given in Table 20.9.

For higher frequencies of 100 mHz and above garnets are used. They have resistivities in excess of $10^8\,\Omega$ m compared with the ferrites, restivities of about $10^3\,\Omega$ m at best. This means that eddy current losses which are dependent on resistivity are minimized. The basic Yttrium Iron Garnet (YIG) composition is $3Y_2O_3.5Fe_2O_3$. This is modified to obtain improved properties such as very low loss and greater temperature stability by the addition of other elements, including aluminium and gadolinium. The garnets are prepared by heating the mixture of oxides under pressure at over 1 300°C for up to 10 h. This material is used in microwave circuits in filters, isolators, circulators and mixtures. Some of their properties are given in Table 20.10.

20.3.3 Nickel–iron alloys

The high permeability of nickel–iron alloys makes them very useful materials for the electronic communications and electrical power engineering industries. This high permeability at low fields (despite the low saturation magnetization) gives scope for minimizing core sizes in a wide range of applications.[16,17]

There are three main groups of high-permeability nickel–iron alloys. The 80% nickel alloys variously called Mumetal and Permalloy have the highest permeability due to the almost zero crystalline anisotropy and magnetostriction at this composition. The commercial alloys have additions of chromium, copper and molybdenum to increase the resistivity and improve the magnetic properties. This material is used in specialized transformers, for magnetic screens and magnetic recording heads.

Table 20.10 GARNET MATERIAL

	J_s(T)	T_c (°C)	ΔH (kA m^{-1})* Maximum
Y Al Fe	0.3–1.76	110–280	45–60
Y Gd Fe	0.67–1.22	280	110–250
Y Gd Al Fe	0.6–1.1	190–250	70–120

* This is the gyromagnetic resonant linewidth ΔH (−3 dB). The values of other parameters for these garnets are:
dielectric constant ε' 13.8–15.2,
$10^4 \tan\delta$ 2.5–3.
Available from Marconi, Lincoln, UK.

Table 20.11 PROPERTIES OF NICKEL–IRON ALLOYS[16]

Alloy	36% Ni	45% Ni	50% Ni	54% Ni	65% Ni	77% Ni
Initial permeability $\times 10^{-3}$	3	6	0.5–11	65	—	60–200
Saturation flux density (T)	1.2	1.6	1.54–1.6	1.5	1.3	0.8
Coercivity force ($A\,m^{-1}$)	10	10	3–10	2.5	2–10	0.5–1
Remanence (T)	0.5	1.0	1.1–1.5	0.7	1.25–0.2	0.5
Resistivity ($\mu\Omega m$)	0.8	0.45	0.4	0.45	0.6	0.6
Density ($kg\,m^{-3}$)	8100	8300	8300	8300	8500	8800
Curie temp. (°C)	280	530	530	550	520	350
Expansion coefficient ($°C^{-1} \times 10^6$)	1	8	10	11	12	13

Available from Telcon Metals, Crawley, UK, Vacuumschmelze and V.D.M., Germany.

The 50% nickel alloys have the highest saturation magnetization of 1.6 T in this range of alloys. They have a higher permeability and better corrosion resistance than silicon–iron alloys but they are more expensive. Another advantage is they have a high incremental permeability over a wide range of polarizing d.c. fields. A wide range of properties can be produced by various processing techniques. Severe cold reduction produces a cube texture and a square hysteresis loop in annealed strip. The properties can be tailored by annealing the material below the Curie temperature in a magnetic field. Applications of this material include chokes, relays and small motors.

The 36% nickel alloys have higher resistivity and are less costly than the 50% alloy but the saturation magnetization and permeability are lower. This alloy is of the Invar type and has a very low coefficient of expansion of $1 \times 10^{-6}°C^{-1}$. The main applications are relays, inductors and high-frequency transformers where the higher resistivity limits the eddy currents. The properties of the various nickel–iron alloys are given in Table 20.11.

20.3.4 Amorphous alloy material

The rapidly solidified alloy materials called metallic glasses are now an established group of soft magnetic materials. These materials are produced by rapid solidification of the alloy at cooling rates around a million degrees centigrade per second. The alloys solidify with a glass-like atomic structure which is a non-crystalline frozen liquid. The rapid solidification is achieved by causing the molten alloy to flow through an orifice on to a rapidly rotating water cooled drum. This can produce sheets of the alloy as little as 10 μm thick and up to a metre or more wide.

There are two main groups of amorphous alloys. The iron-rich magnetic alloys have the highest saturation magnetization among the amorphous alloys and are based on inexpensive raw materials. The other group are the cobalt-based alloys which have very low or zero magnetostriction which leads to the highest permeability and the lowest core loss. All of these alloys have high electrical resistivity, higher than that of conventional crystalline electrical steels. Because of this, eddy current losses are minimized both at 50 Hz and at higher frequencies. They also have other advantages including flexibility without loss of hardness, high tensile strength and better corrosion resistance than similar crystalline alloys. Properties of typical amorphous alloys are given in Table 20.12.

Table 20.12 AMORPHOUS ALLOYS[2]

Amorphous material	J_s (T)	*Curie temperature* °C	*Crystallization* °C	*Electrical resistivity* $\mu\Omega m$	μ_{max}, d.c. annealed	*Coercivity* $A\,m^{-1}$	*Saturation magnetostriction* $\lambda_s \times 10^6$
Iron-based	1.28–1.80	310–415	430–550	1.23–1.37	$35–600 \times 10^3$	1–1.6	19–35
Nickel–iron-based	0.88	350	410	1.38	8×10^5	0.4	12
Cobalt-based	0.55 0.70	200–365	520–550	1.36–1.42	$6–10 \times 10^5$	0.15	<1

These alloys are supplied by Allied Signal, New Jersey, USA.

20.4 High-saturation and constant-permeability alloys

The addition of cobalt to iron increases the saturation intensity. A range of alloys with 24–50% cobalt has saturation up to 10% greater than that of iron. Alloys with around 25% cobalt are used for applications such as magnet pole tips where a combination of good ductility, ease of machining and high-saturation magnetization are required. The permeability and loss characteristics are however inferior to the 50% cobalt alloy. The 49/49/2 Fe/Co/V alloy called Permendur, to which the vanadium has been added to improve the ductility and also substantially increase the resistivity, is used extensively for stators in lightweight generators.

Recent developments, which have improved its mechanical properties, have extended its use to rotor laminations. Other applications include small-volume transformers, relays, diaphragms, loudspeakers and magnet pole tips. The high cost of cobalt restricts the use of these alloys, but they are widely used in aircraft where weight is at a premium. The properties of the alloys are given in Table 20.13.

Table 20.13 IRON–COBALT ALLOYS[16]

Alloy	*Saturation flux density* (T)	*Initial permeability*	*Maximum permeability*	*Coercive force* ($A m^{-1}$)	*Remanence* (T)	*Resistivity* ($\mu\Omega m$)	*Curie temperature* (°C)
24% Co	2.35	250	2000	130	1.5	0.2	925
49/49/2 Co/Fe/V	235	800	7000	950	1.6	0.4	975

Constant-permeability materials are required for applications where a constant inductance is essential for electrical filters or in loading coils for telephone lines. The original materials were in the ternary Fe/Ni/Co series but more recently they have been replaced by the 40–50% nickel Isoperms. They have an addition of 5–15% copper and by cold rolling and heat treatment a preferred orientation is produced. The permeability of 50–60 is constant over a range of fields up to $8 kA m^{-1}$.

20.5 Magnetic powder core materials

The thickness of laminations of ferromagnetic alloy cores must be reduced as the operating frequency is increased above audio range if the increasing loss and reducing permeability caused by eddy currents are to be avoided. However, reduction of thickness of laminations causes increased cost. This may be avoided for many applications up to 200 kHz by the use of magnetic powder cores.[3]

The Permalloys are used in the form of compressed insulated powder cores, the effect of subdivision being to reduce eddy current losses to a minimum. The permeability is also reduced but is made extremely constant, becoming within a small percentage independent of magnetizing force and unaffected by magnetic shock. The properties of such materials are in many ways similar to the constant permeability alloys described in the preceding section. *Sendust*, a brittle alloy of aluminium, silicon and iron, has been similarly used in Japan and Germany. Carbonyl iron powder is used for powder cores mainly at radio frequencies, specially low eddy current losses being obtained on account of the characteristic fine particle size. Some details of these materials are given in Table 20.14.

20.6 Magnetic temperature-compensating materials

Alloys having a marked variation of permeability with temperature are used to compensate for errors in electrical instruments caused by changes in the ambient temperature.

The magnetic permeability of iron and iron alloys decreases with temperature (except for low values of the field), and this causes the readings of electrical meters which depend upon the fluxes

Table 20.14 MAGNETIC POWDER CORE MATERIALS

Material	*Composition*	*Effective initial relative permeability* μ_e	*Typical power loss* kw/m³ (*at* 50 kHz, 100 mT, 25°C)	*Typical applications*
Molybdenum Permalloy	80% Ni–Fe +Mo	125 60	230 500	High Q fixed inductors 0.1 to 200 kHz
Radiometal (high flux)	50% Ni–Fe	125	600	Switch mode power supply chokes and transformers to 250 kHz
		69	650	Mains chokes and filters for suppression of radio frequency interference
Carbonyl iron powder (high frequency)	99.9% Fe	5–25	—	High Q fixed inductors 1–300 MHz. Wide band signal transformers up to 10 GHz. Chokes for RF suppression
Electrolytic iron powder (low frequency)	99% Fe	45–90	3300	Switch mode power supply chokes to 50 kHz. Main chokes for RF suppression
			2400	Dimmer chokes 50 Hz DC electromagnets
Sendust	9.5% Si, 5.5% Al balance Fe.	60	2000	Chokes and inductors

These materials are available from Salford Electrical Instruments, Heywood, UK.

maintained by a constant voltage or current or by a permanent magnet, to decrease with the ambient temperature. To compensate for such errors it is customary to shunt a certain proportion of the magnetic flux passing through the magnetic circuit of the meter by means of an alloy having an unusually high negative temperature coefficient between 0 and 100°C, so that, as the ambient temperature increases, the proportion of the shunted flux decreases, causing more flux to pass through the working air gap of the instrument than otherwise would be the case. By correctly proportioning the shunt component it is possible to render the readings almost completely independent of ambient temperature changes.

Compensation may also be provided for the changes of resistivity of eddy current devices. These alloys have a major application in the compensation of changes in the resistivity with temperature of the copper drag cup in speedometers.

The alloys used are in the nickel–iron series, about 30% nickel, sometimes with additions of chromium, manganese and/or silicon. Details of the characteristics of the alloy are given in Table 20.15.

Table 20.15 THERMOMAGNETIC TEMPERATURE COMPENSATING MATERIALS

	Magnetic flux density at $H = 8 \times 10^3$ A m^{-1} T								
	Temperature °C								
Material	−40	−20	0	20	40	60	80	100	120
Telecon 2799	0.53	0.43	0.33	0.22	0.13	0.05	—	—	—
Telecon 2800	—	—	0.76	0.67	0.59	0.50	0.40	0.29	0.19
Thermoflux 90/100 G	—	—	0.60	0.47	0.33	0.20	0.07	—	—
Thermoflux 65/100 G	—	—	0.43	0.31	0.17	—	—	—	—
Thermoflux 35/100 G	—	—	0.19	0.07	—	—	—	—	—
Carpenter 30	0.60	0.51	0.40	0.28	0.14	0.05	—	—	—
Carpenter 32	1.02	0.97	0.90	0.83	0.75	0.67	0.59	—	—

These materials are supplied by Telecon Metals, UK, Vacuumschmelze, Germany and Carpenter, USA.

20.7 Non-magnetic steels and cast irons

For certain constructional purposes in electrical engineering where magnetic shunting effects have to be avoided there arises a requirement for almost non-magnetic materials possessing certain minimum mechanical properties.

The materials available comprise non-magnetic cast irons, austenitic steels, and certain other sensibly non-magnetic alloys; the choice of materials for any particular purpose is dependent upon the mechanical properties required; e.g. certain intricate stationary parts of electrical machinery would be suitably made from non-magnetic cast iron, while armature straps for high-speed rotors would be made in a high-tensile austenitic alloy steel in order to withstand the dynamic stresses encountered in practice. A high resistivity is sometimes beneficial as well as the possession of virtually non-magnetic properties.

There are two well-known non-magnetic cast irons, one called *Nomag*, a manganese-silicon-nickel-iron with a permeability of 1.04, and a resistivity of 1.40 microhm *m*, and the other *Ni-Resist*, containing lower proportions of manganese and silicon, but a higher proportion of nickel, also a little chromium and copper. These irons with flake graphite are brittle, and can only be used for parts of a simple nature, such as supports which are not subjected to severe mechanical stress. These non-magnetic irons are also made in the spheroidal graphite form e.g. *Nodumag* and *S.G. Ni-Resist*, having the characteristically improved mechanical properties of this type of cast iron.

As examples of austenitic steels, Hadfields 13% manganese steel and the chromium–nickel steels have found considerable use. The stainless steels of the chromium–nickel type are normally non-magnetic but if they are subjected to cold working appreciable magnetic properties may appear. This disadvantage can be overcome by using steels with higher alloy content than the well-known 18/8 type. Besides these materials other non-magnetic austenitic steels have been specially developed to give improved mechanical properties.

Although the originators of some of these steels and cast irons are no longer in business, it is possible to get steelmakers or foundries to produce them to order. Table 20.16 gives details of the non-magnetic cast irons and a number of non-magnetic cast steels.[21]

Table 20.16 NON-MAGNETIC STEELS AND CAST IRONS

						Mechanical properties			
Material	*Nominal composition*	*Relative permeability*	*Resistivity* $\mu\Omega$ m	*Condition*	*Hardness* HB	*Proof stress* MPa	*Max stress* MPa	*Elongation* $L=4\sqrt{A}$ %	*Reduction in area* %
Wrought steels									
18/8 Stainless	8% Ni, 18% Cr and various minor constituents	1.06 or greater	0.72	Austenized	170	278	618	45	50
18/8 Stainless	8% Ni, 18% Cr and various minor constituents	1.4	—	20% cold reduction	280	—	927	25	—
18/8 Stainless	8% Ni, 18% Cr and various minor constituents	about 10.0	—	50% cold reduction	330	—	1313	10	—
18/12 Stainless	12% Ni, 18% Cr etc.	1.03	0.80	Austenized	160	232	618	60	65
18/12 Stainless	12% Ni, 18% Cr etc.	1.1	—	50% cold reduction	—	—	1313	—	—
18/12 Stainless	12% Ni, 18% Cr etc.	1.7	—	90% cold reduction	—	—	—	—	—
25/12 Stainless	12% Ni, 25% Cr etc.	1.01	0.90	Austenized	200	309	695	30	35

Table 20.16 NON-MAGNETIC STEELS AND CAST IRONS—*continued*

Material	*Nominal composition*	*Relative permeability*	*Resistivity* $\mu\Omega$ m	*Condition*	*Mechanical properties*				
					Hardness HB	*Proof stress* MPa	*Max stress* MPa	*Elongation* $L=4\sqrt{A}$ %	*Reduction in area* %
25/12 Stainless	12% Ni, 25% Cr etc.	1.03	—	90% cold reduction	—	—	—	—	—
Foxalloy 101	1% Si, 16–20% Mn, 12–16% Cr, 0.2–1% V	1.01 max	0.75	Austenitic	275	750	960	35	52
Cast steels									
Hadfields Mn	13% Mn, 1% Si	1.03	0.71	Water quenched 1 000°C	—	—	—	—	—
Clyde alloy non-magnetic	8% Ni, 8% Mn, 8% Cr	1.003	0.76	Water quenched 900°C	—	—	—	—	—
Clyde alloy non-magnetic	8% Ni, 4% Mn, 8% Cr	1.003	—	Water quenched 900°C	—	571	927	45	45
Firth Vickers NMC	10% Ni, 5% Mn, 4% Cr	1.008/ 1.03	—	—	—	618	927	45	45
Black alloy 525 (tool bit material)	48% Co, 35% Cr, 14% W carbide, 9% Nb/Ta	1.002/ 1.01	—	—	620	–	450	—	—
Cast irons									
Nomag	7% Mn, 11% Ni, 2.5% Si, 2.7% C	1.03/ 1.05	1.40	Stress relieved	120/150	–	~185	0	–
Nodumag	7% Mn, 11% Ni, 2.5% Si, 2.7% C	1.03	1.10	Stress relieved	120/150	309	432	15	—
Ni-Resist Type 2	Ni 20%, Si 2.5%	1.03	1.70	Stress relieved	150	—	185	0	—
S.G. Ni-Resist Type D-2	Mn 1%, Cr 2%, C 2%	1.03	1.00	Stress relieved	140	232	415	15	—

Wrought steels are available from Stocksbridge Engineering Steels, Stocksbridge, UK and Startan Redheugh, Gateshead, UK. Black alloy is available from Brunner, Acton, London.

Appendix

Units and definitions

Magnetic poles

The concept of magnetic poles is used to explain the behaviour of magnetized bodies acting on one another and in the earth's magnetic field. Like magnetic poles repel each other and unlike poles attract.

Magnetic dipole

A magnetic dipole is an elementary pair of unlike poles and can be represented by an infinitesimal current loop.

Magnetic moment m

For a magnetic dipole the magnetic moment is the product of the current and the loop area. For a magnetized body the magnetic moment is the sum of all the magnetic dipole moments and is equal to ml where l is the distance between the poles.

Magnetic field strength H

The magnetic field strength H at a point is an axial vector quantity associated with the magnetic flux density in a magnetic field. The unit of magnetic field is the ampere per metre ($A\,m^{-1}$), which is the (axial) field inside an infinitely long solenoid of one turn per metre carrying a current of one ampere.

Magnetization M

When a magnetic field is applied to a magnetic material the material becomes magnetized. The magnitude of this magnetization M is equal to the total magnetic moment divided by the volume. The units of M are ampere per metre ($A\,m^{-1}$).

Polarization J

This is the name given to the product $\mu_0 M$, and it has the units of tesla (T).

Saturation magnetization M_s and polarization J_s

These are the maximum possible values of the magnetization and polarization for a given material at a given temperature. The saturation polarization J_s is sometimes called B_s.

Magnetization per unit mass σ

The value of σ is usually the saturation value and is equal to M/ρ where ρ is the density. The units are joule/(tesla kg).

Magnetic flux density B (or magnetic induction)

The magnetic flux density B at a point is a vector quantity arising from the magnetic field and the magnetization of the medium. It is given by:

$$B = \mu_0 H + \mu_0 M$$

or

$$B = \mu_0 H + J$$

where μ_0 is the magnetic constant. The units of B are tesla (T) or weber/(metre)^2 ($Wb\,m^{-2}$).

Magnetic constant μ_0

This constant μ_0 is equal to $4\pi \times 10^{-7}$ Henries m^{-1}. For practical purposes this constant when multiplied by the field strength equals the flux density in vacuo. (It was in the past called the permeability of free space.)

Magnetic flux φ

The magnetic flux ϕ is the sum over an area A of the magnetic flux density and $\phi = BA$. The unit of flux is the weber (Wb).

Magnetic susceptibility κ

The magnetic susceptibility κ of a material is the ratio of the magnetization M to the magnetic field H producing it. This quantity κ is the magnetic susceptibility per unit volume and is dimensionless.

Mass susceptibility χ

The magnetic susceptibility per unit mass or mass susceptibility χ is given by κ/ρ, where ρ is the density of the material. It has the units of $m^3\,kg^{-1}$.

Magnetic permeability μ

The permeability μ of a medium is the ratio of the magnetic flux B to the magnetic field H producing

it. For practical purposes the value of μ is divided by the magnetic constant μ_0 to give the relative magnetic permeability μ_r which is dimensionless. For strongly magnetic materials the value of μ_r varies with the value of the magnetic field. The values of μ_i, the initial permeability, and μ_{max}, the maximum permeability, are widely quoted parameters for magnetic materials.

Curie point T_c

The Curie point, or temperature, (T_c) is the temperature below which a material is ferromagnetic or ferrimagnetic and above which it is paramagnetic.

Néel point N_c

The Neel point or temperature is the temperature below which a material is antiferromagnetic and above which it is paramagnetic.

Magnetic hysteresis

This is a phenomenon by which the magnetization of a material depends not only on the magnetizing field but also on the previous magnetic history. The magnetic flux B always lags behind magnetic field H in a material showing hysteresis. The complete B–H curve, or loop, produced by increasing H from zero to a maximum value, reducing to zero and then repeating with H in the negative sense is termed the hysteresis loop, and the dissipation of energy associated with it, the hysteresis loss. The hysteresis loss per unit volume is given by (area of the loop in $B \times H$) joules.

Remanence B_r

This is the value of the magnetic flux density remaining in a material in a closed magnetic circuit following magnetization to saturation and subsequent removal of the magnetic field.

Coercivity H_c

This is the magnetic field strength when a material is brought from saturation to the point where the flux density B or magnetization M is reduced to zero. In a graphical representation it is the value corresponding to the intersection of the B curve or the M with the H axis. Two cases must be distinguished. When the value of B is reduced to zero the coercivity is called H_{cB} and when the value of M(or J) is reduced to zero the value is called H_{cM} (or H_{cJ}). The quantity H_{cJ} is sometimes called H_{ci}.

Energy Product and $(BH)_{max}$

The energy product is the product of the flux density and the field strength at any point of a demagnetization curve for a permanent magnet. The maximum value of the product is called $(BH)_{max}$. It is directly related to the stored energy per unit volume of the material. The units of $(BH)_{max}$ are joules/(metre)^3.

Magnetostriction

Elastic deformation which accompanies a change in the magnetization of a material. This results in changes of length or volume.

Magnetic units and conversion factors

Authors and publishers of current literature on magnetism and magnetic materials have been very slow in adopting SI (systeme international) units in place of the centimetre gram second (c.g.s.) electromagnetic units previously used. Conversion of magnetic units between the two systems are therefore frequently required, as well as care in using equations which are different for the two systems. The relation between the relevant c.g.s. electromagnetic units and the SI (rationalized m.k.s.) units is given in Table 20.17.

Table 20.17 RELATION BETWEEN SI UNITS AND C.G.S. UNITS OF MAGNETIC QUANTITIES

Quantity	*c.g.s. unit*	*SI unit*	*Conversion factor**
Magnetic field H	Oersted (Oe)	amperes per metre ($A\,m^{-1}$)	$\times 10^3/4\pi$
Magnetic flux ϕ	Maxwell (or line)	Weber (Wb)	$\times 10^{-8}$
Flux density B	Gauss (Gs)	Tesla (T)	$\times 10^{-4}$
Magnetomotive force	Oersted cm or Gilbert	amperes	$\times 10/4\pi$
Polarization	I or J e.m.u.	J Tesla (T)	$\times 4\pi.10^{-4}$
Magnetization	I or J e.m.u.	M amperes per metre	$\times 10^3$
Maximum energy product $(BH)_{max}$	M Gs Oe	$J\,m^{-3}$ or $T\,A\,m^{-1}$	$\times 10^5/4\pi$
Magnetic moment m	e.m.u.	Weber metre (Wb m)	$\times 4\pi\,10^{-10}$
Magnetic constant μ_0	1	Henry m^{-1} ($H\,m^{-1}$)	$\times 4\pi\,10^{-7}$
Resistivity ρ	ohm.cm	ohm.m	$\times 10^{-2}$

* The number by which the quantity in c.g.s. units must be multiplied to obtain the quantity in SI units.

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See also 7, p 146 and BS 5884, 1987, see below.

Standards

22. A series of International (IEC) and equivalent British Standards (BS) have been published for the Classification, Specification and Methods of Test for Magnetic Materials. The IEC series are numbered 404 and the equivalent BS series are 6404. In addition BS 4727, part I Group 07, 1991 is the standard for 'Magnetism terminology' and BS 5884, 1987. Methods for determination of relative magnetic permeability of feebly magnetic materials.

21 Mechanical testing

21.1 Hardness testing

21.1.1 Brinell hardness

An indenter comprising a hardened steel ball of diameter D mounted in a suitable holder is pushed into the material under test by a force F. The diameter of the indentation left in the surface of the material after removal of the load is measured in two directions at right angles. The area of the curved surface of the indentation is calculated from the mean diameter, d, the indentation being considered as a segment of a sphere of diameter D. The Brinell hardness is the quotient obtained by dividing the load, symbol f, expressed in kilograms-force, by the surface area of the indentation expressed in square millimetres.

Symbols:

F = force (N)

f = load symbol (kgf)

D = diameter of ball in millimetres (mm)

d = mean diameter of indentation in millimetres (mm)

$$\text{HB} = \text{Brinell Hardness} = \frac{0.102 \times 2F}{\pi D[D - \sqrt{(D^2 - d^2)}]} = \frac{2f}{\pi D[D - \sqrt{(D^2 - d^2)}]}$$

$$h = \text{depth of indentation in millimetres} = \frac{f}{\pi D(\text{HB})} \text{ (mm)}$$

The symbol HB is supplemented by numbers indicating the diameter of the ball used and the load applied. Thus 226 HB 10/3000 indicates that a Brinell hardness of 226 was obtained by using a 10 mm diameter ball with a load symbol of 3000 kgf. If the time of duration of load differs from the standard 10–15 seconds, a further number is added to show the duration of the load in seconds.

RELATION OF LOAD TO BALL DIAMETER

The choice of force and ball diameter to be used in a Brinell test is determined by two factors:

1. the value of the ratio f/D^2, and
2. the size of the indentation which provides optimum accuracy.

The same value of f/D^2 will, in principle, give the same hardness value for different loads and the load used in practice depends on the nature and the hardness of the material under test. Four standard values of f/D^2, i.e. 30, 10, 5 and 1, have been adopted. Combinations of load and diameter are given in BS 240:1986 (*see* Table 21.1).

21.1.2 Rockwell hardness

An indenter of the standard type comprising a diamond cone or hardened steel ball mounted rigidly in a suitable holder, is forced into the test piece under a preliminary load F_0. When

Table 21.1 CORRELATED VALUES OF LOAD AND BALL DIAMETER FROM BS 240:1986

Diameter of ball	*Test force – F (N) Load symbol – f (kgf)*							
	$f/D^2 = 1$		$f/D^2 = 5$		$f/D^2 = 10$		$f/D^2 = 30$	
mm	*F*	*f*	*F*	*f*	*F*	*f*	*F*	*f*
1	9.807	1	49.03	5	98.07	10	294.2	30
2	39.23	4	196.1	20	392.3	40	1177	120
2.5	61.29	6.25	306.5	31.25	612.9	62.5	1839	187.5
5	245.2	25	1226	125	2452	250	7365	750
10	980.7	100	4903	500	9807	1000	29420	3000

Notes: (1) The maximum depth of indentation shall not exceed $\frac{1}{8}$ of the thickness of the test piece, according to BS 240:1986 or $\frac{1}{10}$ of the thickness according to ASTM E10-84.
(2) In the USA Specification ASTM E10-84 only f/D^2 values of 30, 15 and 5 with a 10 mm ball are regarded as standard.

The following values of f/D^2 are recommended for some typical materials:

Material	*Typical HB*	f/D^2
Steel, Ni alloys, cast iron and Ti alloys	>100	30
Cu, Co alloys and Al alloys	30–200	10
Al	10–100	5
Pb, Sn	3–20	1

Note: The test is not suitable for materials with a hardness greater than 600 HB. The use of tungsten carbide balls is preferred for HB>350 and is mandatory for HB>450.

equilibrium has been reached, an indicating device which follows the movement of the indenter and so responds to changes in depth of penetration of the indenter is set to a datum position.

While the preliminary load is still applied, it is augmented by an additional load with resulting increase in penetration of the indenter. When equilibrium has again been reached, the additional load is removed but the preliminary load is maintained.

Removal of the additional load allows a partial recovery, so reducing the depth of penetration. The permanent increase in depth of penetration, *e*, resulting from application and removal of the additional load is used to deduce the Rockwell hardness number by means of the equation:

$$HR = E - e$$

where:

HR = Rockwell hardness number
E = a constant depending on the form of indenter:
100 units when a diamond cone indenter is used
130 units when a steel ball indenter is used

A variety of indenters and loads are used to give several scales of hardness, e.g. 60HRC represents a Rockwell hardness of 60 on scale C. The various scales are defined in Table 21.2.

Table 21.2 ROCKWELL HARDNESS SCALES

Scale symbol		*Major load* kN	kgf	*Dial figures*	*Typical applications of scales*
B	$\frac{1}{16}$ in (1.588 mm) ball	0.98	100	Red	Copper alloys, soft steels, aluminium alloys, malleable iron, etc.
C	Diamond	1.47	150	Black	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than HRB100
A	Diamond	0.59	60	Black	Cemented carbides, thin steel, and shallow case-hardened steel
D	Diamond	0.98	100	Black	Thin steel and medium case hardened steel, and pearlitic malleable iron
E	$\frac{1}{8}$ in (3.175 mm) ball	0.98	100	Red	Cast iron, aluminium and magnesium alloys, bearing metals
F	$\frac{1}{16}$ in (1.588 mm) ball	0.59	60	Red	Annealed copper alloys, thin soft sheet metals

Table 21.2 ROCKWELL HARDNESS SCALES—*continued*

Scale symbol		*Major load* kN	kgf	*Dial figures*	*Typical applications of scales*
G	$\frac{1}{16}$ in (1.588 mm) ball	1.47	150	Red	Malleable irons, copper–nickel–zinc and cupro-nickel alloys. Upper limit HRG 92 to avoid possible flattening of ball
H	$\frac{1}{8}$ in (3.175 mm) ball	0.59	60	Red	Aluminium, zinc, lead
K	$\frac{1}{8}$ in (3.175 mm) ball	1.47	150	Red	
L	$\frac{1}{4}$ in (6.350 mm) ball	0.59	60	Red	
M	$\frac{1}{4}$ in (6.350 mm) ball	0.98	100	Red	
P	$\frac{1}{4}$ in (6.350 mm) ball	1.47	150	Red	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that does not give anvil effect
R	$\frac{1}{2}$ in (12.70 mm) ball	0.59	60	Red	
S	$\frac{1}{2}$ in (12.70 mm) ball	0.98	100	Red	
V	$\frac{1}{2}$ in (12.70 mm) ball	1.47	150	Red	

Notes: (1) The preliminary load is 10 kgf for all scales.
(2) The diamond indenter is conical with an included angle of $120 \pm 0.1°$ with a tip rounded to a radius of 0.20 mm.
(3) ASTM E18-84 standard gives values in kgf. Newton values are conversions.
Relevant standards are BS 891: Part 1: 1962 (1981) and ASTM E18-84 in the USA.

21.1.3 Rockwell superficial hardness

This test is similar in principle to the Rockwell test, but in order to keep the depth of impression small the minor load is restricted to 3 kg. It is used for thin specimens and for nitrided steels, etc. The following scales are used.

Table 21.3 ROCKWELL SUPERFICIAL HARDNESS SCALES

Scale	*Penetrator*	*Minor load* kgf	N	*Major load* kgf	kN
15-N	Diamond cone	3	29.4	15	0.14
30-N	Diamond cone	3	29.4	30	0.29
45-N	Diamond cone	3	29.4	45	0.44
15-T	$\frac{1}{16}$ in (1.588 mm) steel ball	3	29.4	15	0.14
30-T	$\frac{1}{16}$ in (1.588 mm) steel ball	3	29.4	30	0.29
45-T	$\frac{1}{16}$ in (1.588 mm) steel ball	3	29.4	45	0.44

Relevant standards are BS: 4175: Part 1: 1967 (1985) and ASTM E10-84 in the USA.

21.1.4 Vickers hardness test

A diamond indenter, in the form of a right pyramid with a square base and an angle of 136° between opposite faces, is forced into the material under a load F. The two diagonals, d_1 and d_2 of the indentation left in the surface of the material after removal of the load are measured and their arithmetic mean d calculated. The area of the sloping surface of the indentation is calculated, the indentation being considered as a right pyramid with a square base of diagonal d and vertex angle of 136°.

The Vickers hardness is the quotient obtained by dividing the load F, expressed in kilograms-force, by the sloping area of the indentation expressed in square millimetres.

Symbols:
F = load in kilograms force (kgf) where 1 kgf = 9.806 65 N
d = arithmetic mean of the two diagonals d_1 and d_2 in millimetres (mm)
HV = Vickers hardness
$= 2F \sin (136°/2)d^2$
$= 1.854F/d^2$

The loads employed vary from 1 to 100 kgf and are maintained from 10 to 15 seconds. Hardness numbers are expressed as 440 HV30 for example where a hardness of 440 is measured using a 30 kgf load.

Relevant standards are BS 427: Part 1: 1961 (1981) and ASTM E92-82 (1987) in the USA.

21.1.5 Micro-hardness testing

Standards ASTM E384-84

A diamond indenter of specified geometry is forced into the surface of the test piece using a calibrated machine with a test load of 1–1 000 gf to give a micro-indentation, the diagonals of which are subsequently measured by means of a microscope.

Symbols:
HK $= 14\,229\ P_1/d_1^2$
where HK = Knoop hardness
P_1 = load in gf
and d_1 = length of long diagonal of indentation in μm
HV $= 1854.4\ P_1/d_1^2$
where HV = Vickers hardness
P_1 = load in gf
and d_1 = mean length of the diagonals of the indentation in μm

Indenters
Knoop: A highly polished, pointed, rhombic-based pyramidal diamond with included longitudinal edge angles of 172.5° and 130°.
Vickers: A highly polished, pointed, square-based pyramidal diamond with face angles of 136°.

21.1.6 Hardness conversion tables

Table 21.4 only applies to steel of uniform chemical composition and uniform heat treatment, and is not recommended for non-ferrous metals or for case-hardened steels.

Table 21.4 APPROXIMATE CONVERSION OF HARDNESS VALUES
Non-austenitic steels (ASTM E140)

		Rockwell hardness No.			
Vickers hardness No. HV	*Brinell* 3000 kg *load* 10 mm *ball* HB	*C Scale* 150 kg *load diamond cone* HRC	*A scale* 60 kg *load diamond cone* HRA	*Superficial* 30–*N* 10 kg *load diamond cone*	*Scleroscope hardness No.*
100	95	—	43	—	—
120	115	—	46	—	—
140	135	—	50	—	21
160	155	—	53	—	24
180	175	—	56	—	27
200	195	—	58	—	30
220	215	—	60	—	31
240	235	20.3	60.7	41.7	34
260	255	24.0	62.4	45.0	37
280	275	27.1	63.8	47.8	40
300	295	29.8	65.2	50.2	42
320	311	32.2	66.4	52.3	45
340	328	34.4	67.6	54.4	47
360	345	36.6	68.7	56.4	50
380	360	38.8	69.8	58.4	52
400	379	40.8	70.8	60.2	55
420	397	42.7	71.8	61.4	57
440	415	44.5	72.8	63.5	59
460	433	46.1	73.6	64.9	62
480	452	47.7	74.5	66.4	64

Table 21.4 APPROXIMATE CONVERSION OF HARDNESS VALUES— *continued*
Non-austenitic steels (ASTM E140)

Vickers hardness No. HV	*Brinell** 3 000 kg *load* 10 mm *ball* HB	*Rockwell hardness No.* C Scale 150 kg *load diamond cone* HRC	*Rockwell hardness No.* A scale 60 kg *load diamond cone* HRA	*Rockwell hardness No.* Superficial 30–*N* 10 kg *load diamond cone*	*Scleroscope hardness No.*
500	471	49.1	75.3	67.7	66
520	487	50.5	76.1	69.0	67
540	507	51.7	76.7	70.0	69
560	525	53.0	77.4	71.2	71
580	545	54.1	78.0	72.1	72
600	564	55.2	78.6	73.2	74
620	582	56.3	79.2	74.2	75
640	601	57.3	79.8	75.1	77
660	620	58.3	80.3	75.9	79
680	638	59.2	80.8	76.8	80
700	656	60.1	81.3	77.6	81
720	670	61.0	81.8	78.4	83
740	684	61.8	82.2	79.1	84
760	698	62.5	82.6	79.7	86
780	710	63.3	83.0	80.4	87
800	722	64.0	83.4	81.1	88
820	733	64.7	83.8	81.7	90
840	745	65.3	84.1	82.2	91
860	—	65.9	84.4	82.7	92
880	—	66.4	84.7	83.1	93
900	—	67.0	85.0	83.6	95
920	—	67.5	85.3	84.0	96
940	—	68.0	85.6	84.4	97

* Brinell values greater then 480 are determined with a carbide ball.

Table 21.5 APPROXIMATE CONVERSION OF HARDNESS VALUES
Aluminium and its alloys

HV 10 kg	*Brinell** HB	*Rockwell superficial* HR 15T	30T	45T	HV 10 kg	*Brinell** HB	*Rockwell superficial* HR 15T	30T	45T
20	19.4	2.3	—	—	80	74.6	75.3	44.1	—
24	23.1	18.1	—	—	84	78.3	76.5	46.9	—
28	26.8	29.5	—	—	88	82.0	77.6	49.4	—
32	30.5	38.2	—	—	92	85.7	78.6	51.8	—
36	34.2	45.0	—	—	96	89.4	79.5	54.0	—
40	37.8	50.3	—	—	100	93.0	80.3	55.9	—
44	41.5	54.8	—	—	104	96.7	81.1	57.7	—
48	45.2	58.6	5.2	—	108	100.4	81.8	59.4	—
52	48.9	61.8	12.6	—	112	104.1	82.5	60.9	—
56	52.6	64.5	19.1	—	116	107.8	83.1	62.4	—
60	56.2	66.9	24.5	—	120	111.4	83.7	63.8	39.0
64	59.9	69.0	29.4	—	124	115.1	84.3	65.0	41.2
68	63.6	70.8	33.7	—	128	118.8	84.8	66.2	43.3
72	67.3	72.5	37.6	—	132	122.5	85.3	67.4	45.2
76	71.0	74.0	41.0	—	136	126.2	85.7	68.5	47.1

* The ratio $\frac{\text{load}}{(\text{dia. of ball})^2}$ for the Brinell tests was 5 for Brinell hardnesses of 20–60 and 10 for hardnesses above 60.

Table 21.5 APPROXIMATE CONVERSION OF HARDNESS VALUES—*continued*
Aluminium and its alloys

HV 10 kg	*Brinell** HB	*Rockwell superficial* HR 15*T*	30*T*	45*T*	HV 10 kg	*Brinell** HB	*Rockwell superficial* HR 15*T*	30*T*	45*T*
140	129.8	86.2	69.4	48.8	172	159.3	88.3	75.8	59.6
144	133.5	86.6	70.4	50.4	176	163.0	89.2	76.4	60.7
148	137.2	86.9	71.3	51.9	180	166.6	89.4	77.0	61.7
152	140.9	87.3	72.1	53.3	184	170.3	89.7	77.6	62.7
156	144.6	87.6	72.9	54.7	188	174.0	89.9	78.1	63.6
160	148.2	88.0	73.7	56.0	192	177.7	90.1	78.7	64.5
164	151.9	88.3	74.4	57.3	196	181.4	90.3	79.2	65.4
168	155.6	88.6	75.1	58.4	200	185.0	90.6	79.7	66.2

*The ratio $\frac{\text{load}}{(\text{dia. of ball})^2}$ for the Brinell tests was 5 for Brinell hardnesses of 20–60 and 10 for hardnesses above 60.

Table 21.6 APPROXIMATE CONVERSION OF HARDNESS VALUES
Brass (ASTM E140-86)

	Rockwell hardness No.		*Rockwell superficial hardness No.*			*Brinell hardness No.*		*Rockwell hardness No.*		*Rockwell superficial hardness No.*			*Brinell hardness No.*
HV	*B scale*, 100 kg *load*, $\frac{1}{16}$ in *ball*	*F scale*, 60 kg *load*, $\frac{1}{16}$ in *ball*	15-*T scale*, 15 kg *load*, $\frac{1}{16}$ in *ball*	30-*T scale*, 30 kg *load*, $\frac{1}{16}$ in *ball*	45-*T scale*, 45 kg *load*, $\frac{1}{16}$ in *ball*	500 kg *load*, 10 mm *ball*	HV	*B scale*, 100 kg *load*, $\frac{1}{16}$ in *ball*	*F scale*, 60 kg *load*, $\frac{1}{16}$ in *ball*	15-*T scale*, 15 kg *load*, $\frac{1}{16}$ in *ball*	30-*T scale*, 30 kg *load*, $\frac{1}{16}$ in *ball*	45-*T scale*, 45 kg *load*, $\frac{1}{16}$ in *ball*	500 kg *load*, 10 mm *ball*
45	—	40.0	—	—	—	42	120	67.0	95.5	—	61.0	41.0	106
47	—	45.0	—	—	—	44	124	69.0	96.5	—	62.5	43.0	110
49	—	49.0	54.5	—	—	46	128	71.0	97.5	—	63.5	45.0	113
52	—	53.5	57.0	—	—	48	132	73.0	98.5	84.5	65.0	46.5	116
56	—	58.8	60.0	15.0	—	52	136	74.5	99.5	85.0	66.0	48.0	120
60	10.0	63.0	62.5	20.5	—	55	140	76.0	100.5	85.5	67.0	50.0	122
64	15.5	66.8	65.0	22.5	—	59	144	77.8	101.5	86.0	68.0	51.5	126
68	21.5	70.0	67.0	30.0	—	62	148	79.0	102.5	—	69.0	53.0	129
72	27.5	73.2	69.0	34.0	—	64	152	80.5	103.0	—	—	54.0	133
76	32.5	76.0	70.5	38.0	4.5	68	156	82.0	104.0	87.0	70.5	55.5	136
80	37.5	78.6	72.0	41.0	10.0	72	160	83.5	—	—	71.5	56.5	139
84	42.0	81.2	73.5	44.0	14.5	76	164	85.0	105.5	—	72.0	58.0	142
88	46.0	83.5	75.0	47.0	19.0	79	168	86.0	106.0	88.0	73.0	59.0	146
92	49.5	85.4	76.5	49.0	23.0	82	172	87.5	106.5	—	73.5	60.0	149
96	53.0	87.2	77.5	51.5	26.5	85	176	88.5	107.0	—	—	61.0	152
100	56.0	89.0	78.5	53.5	29.5	88	180	90.0	107.5	—	75.0	62.0	156
104	58.0	90.5	79.5	55.0	32.0	92	184	91.0	—	—	75.5	63.0	159
108	61.0	92.0	—	57.0	34.5	95	188	92.0	—	89.5	—	64.0	162
112	63.0	93.0	81.0	58.5	37.0	99	192	93.0	—	—	77.0	65.0	166
116	65.0	94.5	82.0	60.0	39.0	103	196	93.5	110.0	90.0	77.5	66.0	169

Note: $\frac{1}{16}$ in = 1.588 mm.

Table 21.7 APPROXIMATE CONVERSION OF HARDNESS VALUES
Hard metals

Vickers diamond hardness, 50 kg *load*	*Rockwell A scale* 60 kg *load: diamond cone*	*Rockwell C scale* 150 kg *load: diamond cone*
1 750	92.4	80.5
1 700	92.0	79.8
1 650	91.7	79.2
1 600	91.3	78.4
1 550	90.9	77.7
1 500	90.5	77.0
1 450	90.1	76.2
1 400	89.7	75.4
1 350	89.3	74.6
1 300	88.9	73.8
1 250	88.5	73.0
1 200	88.1	72.2
1 150	87.6	71.3
1 100	87.0	70.4
1 050	86.4	69.4
1 000	85.7	68.2
950	85.0	66.6
900	84.0	64.6
850	82.8	—

Table 21.8 APPROXIMATE CONVERSION OF HARDNESS VALUES FOR NICKEL AND HIGH NICKEL ALLOYS (E140-86)

Vickers hardness No. HV	*Brinell hardness No.* HB	*Rockwell hardness no.*		
		A. scale	*B scale*	*C scale*
Vickers indenter 1, 5, 10 *and* 30 kgf	10 mm *ball* 3000 kgf	*Diamond penetrator* 60 kgf	$\frac{1}{16}$ in *ball* 100 kgf	*Diamond penetrator* 150 kgf
77	77	—	30	—
79	79	—	34	—
83	83	—	38	—
87	87	—	42	—
91	91	—	46	—
95	95	—	50	—
100	100	—	54	—
106	106	—	58	—
112	111	39.0	62	—
119	118	41.0	66	—
126	125	43.0	70	—
135	134	45.5	74	—
145	144	47.5	78	—
157	155	50.0	82	—
171	168	52.5	86	—
188	184	55.0	90	—
209	204	57.5	94	—
234	228	60.5	98	20.0
248	241	61.5	100	22.5
285	275	64.5	—	28.5
326	313	67.5	—	34.0
362	346	69.5	—	38.0
404	382	71.5	—	42.0
452	425	73.5	—	46.0
481	450	74.5	—	48.0
513	—	75.5	—	50.0

Note: $\frac{1}{16}$ in ≡ 1.588 mm.

21.2 Tensile testing

21.2.1 Standard test pieces

Table 21.9 DIMENSIONS OF CIRCULAR SECTION TEST PIECES—BRITISH STANDARDS BS 18:1987
Gauge length $L_0 = 5.65\sqrt{S_0}$. Minimum parallel length $L_c = 5.5d$

Cross-sectional area S_0 mm²	*Diameter d* mm	*Gauge length* L_0 mm	*Minimum parallel length* L_c mm	*Minimum transition radius r* mm
400	22.56	113	124	23.5
200	15.96	80	88	15
150	13.82	69	76	13
100	11.28	56	62	10
78.5	10.00	50	55	9
50	7.98	40	44	8
25	5.64	28	31	6
19.6	5.00	25	28	6
12.5	3.99	20	22	4

Table 21.10 DIMENSIONS OF CIRCULAR SECTION TEST PIECES—AMERICAN STANDARDS ASTM E8M-88
Gauge length $L_0 = 5d$

Diameter d mm	*Gauge length* L_0 mm	*Minimum parallel length* L_c mm	*Minimum transition radius r* mm
12.50	62.5±0.1	75	10
9.00	45.0±0.1	54	8
6.00	30.0±0.1	36	6
4.00	20.0±0.1	24	4
2.50	12.5±0.1	20	2

Table 21.11 DIMENSIONS OF RECTANGULAR SECTION TEST PIECES—BRITISH STANDARDS BS 18:1987

Width b mm	*Gauge length* L_0 mm	*Minimum parallel length* L_c mm	*Minimum transition radius r* mm	*Approximate total length* L_t mm
50	200	225	25	450
25	100	112.5	25	300
20	80	90	25	250
12.5	50	56.25	25	200
6	25	28	12	100
3	12.5	14	6	50

Table 21.12 DIMENSIONS OF RECTANGULAR SECTION TEST PIECES—AMERICAN STANDARDS ASTM E8M-88

Width b mm	*Gauge length* L_0 mm	*Minimum parallel length* L_c mm	*Minimum transition radius r* mm	*Approximate total length* L_t mm
40.0±0.2	200±0.2	225	25	450
12.5±0.2	50±0.1	57	12.5	200
6.0±0.1	25±0.1	32	6	100

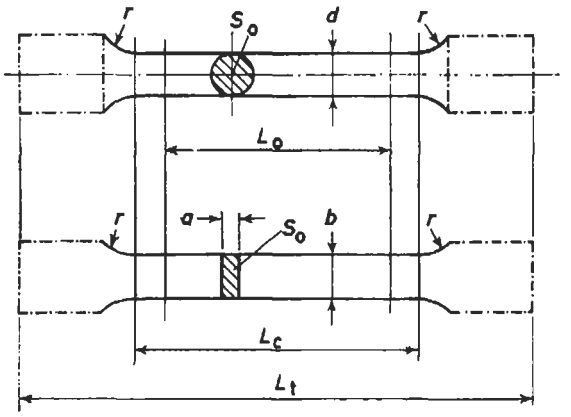
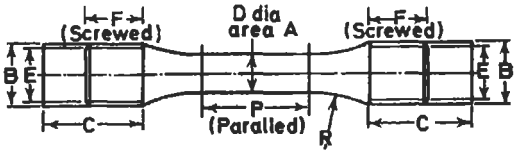


Figure 21.1 *Test pieces of circular and rectangular cross-section*
BS 18:Part 2:1987

Table 21.13 STANDARD TENSILE TEST PIECES FOR CAST IRON–BRITISH STANDARDS BS: 1452: 1977



Dimensions of machined tensile test piece

Gauge diameter D		*Minimum parallel length P*	*Minimum radius R*		*Plain ends*		*Screwed ends*	
Nominal value	*Machining tolerance**		*Nominal value*	*Machining tolerance*	*Minimum diameter B*	*Minimum length C*	*Minimum diameter at root of thread E*	*Minimum length F*
mm	mm	mm	mm	mm	mm	mm	mm	mm
20	±0.5	55	25	−0, +5	25	65	25	30

* If it is desired to calculate the tensile strength on the basis of the nominal diameter, the machining tolerance shall be 0.10 mm.

Note: With screwed ends, any form of thread may be used provided that the diameter at the root of the thread is not less than that specified.

Table 21.14 STANDARD TENSILE TEST PIECES FOR CAST IRON—AMERICAN STANDARDS
ASTM E8-88 AND E8M-88

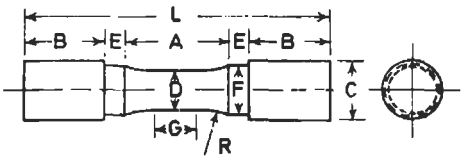


Table 21.14 STANDARD TENSILE TEST PIECES FOR CAST IRON—AMERICAN STANDARDS ASTM E8-88 AND E8M-88—*continued*

		Dimensions					
		Specimen 1		*Specimen 2*		*Specimen 3*	
		in	mm	in	mm	in	mm
G	Length of parallel	Shall be equal to or greater than diameter *D*					
D	Diameter	0.500 ± 0.010	12.5 ± 0.2	0.750 ± 0.015	20.0 ± 0.40	1.25 ± 0.02	30.0 ± 0.60
R	Radius of fillet, min.	1	25	1	25	2	50
A	Length of reduced section, min.	$1\frac{1}{4}$	32	$1\frac{1}{2}$	38	$2\frac{1}{2}$	60
L	Overall length, min.	$3\frac{3}{4}$	95	4	100	$6\frac{3}{8}$	160
B	Length of end section, approximate	1	25	1	25	$1\frac{3}{4}$	45
C	Diameter of end section, approximate	$\frac{3}{4}$	20	$1\frac{1}{8}$	30	$1\frac{7}{8}$	48
E	Length of shoulder, min.	$\frac{1}{4}$	6	$\frac{1}{4}$	6	$\frac{5}{16}$	8
F	Diameter of shoulder	$\frac{5}{8} \pm \frac{1}{64}$	16.0 ± 0.40	$1\frac{5}{16} \pm \frac{1}{64}$	24.0 ± 0.40	$1\frac{7}{16} \pm \frac{1}{64}$	36.5 ± 0.40

Note: The reduced section and shoulders (dimensions *A*, *D*, *E*, *F*, *G* and *R*) shall be as shown, but the ends may be of any form to fit the holders of the testing machine in such a way that the load shall be axial. Commonly the ends are threaded and have the dimensions *B* and *C* given above. Imperial units are E8-88 and metric units are E8M-88.

21.3 Impact testing of notched bars

21.3.1 Izod test

The test consists of measuring the energy absorbed in breaking a notched test piece by one blow from a striker carried by a pendulum. The test piece is gripped vertically with the root of the notch in the same plane as the upper face of the grips. The blow is struck on the same face as the notch and at a fixed height above it. Tests are usually performed at the ambient temperature of the test house.

TEST PIECES

The standard test pieces are either 10 mm square or 0.45 inches (11.4 mm) diameter cross-section. Complete dimensions are shown in Table 21.15. The notch profile is shown in Figure 21.2.

Table 21.15 DIMENSIONS OF IZOD IMPACT TEST PIECES—BRITISH STANDARD BS 131:PART 1:1961 (1989) AND AMERICAN STANDARD ASTM E23-86

Item	*Square section*		*Circular section*	
	Nominal dimension			
	mm	in *equivalent*	in	mm *equivalent*
Minimum overall length of test piece				
1 Notch	70[1]	2.75	2.8[1]	71
2 Notch	98	3.86	3.9	99
3 Notch	126[2]	4.96	5.0[3]	127
Width	10	0.394	0.45 dia.	11.48 dia
Thickness	10	0.394		
Root radius of notch	0.25	0.010	0.010	0.25
Maximum depth below notch	8	0.315	0.32	8.1
Distance of plane of symmetry of notch from free end of test piece and from the adjacent notch	28	1.1	1.1	28
Angle of notch	45°		45°	

Notes: (1) American Standard overall length 75 mm (2.952 in).
(2) American Standard overall length 131 mm (5.157 in).
(3) American Standard overall length 137 mm (5.375 in).

PRESENTATION OF RESULTS

When standard test pieces are used the following symbols are used in reporting the results of Izod tests:

I for Izod
S for square section
Rs for circular cross-section with straight notch
E.G. I120S: x ft lbf

An energy of x ft lbf was obtained from an Izod test with a striking energy of 120 ft lbf using a square section test piece.†

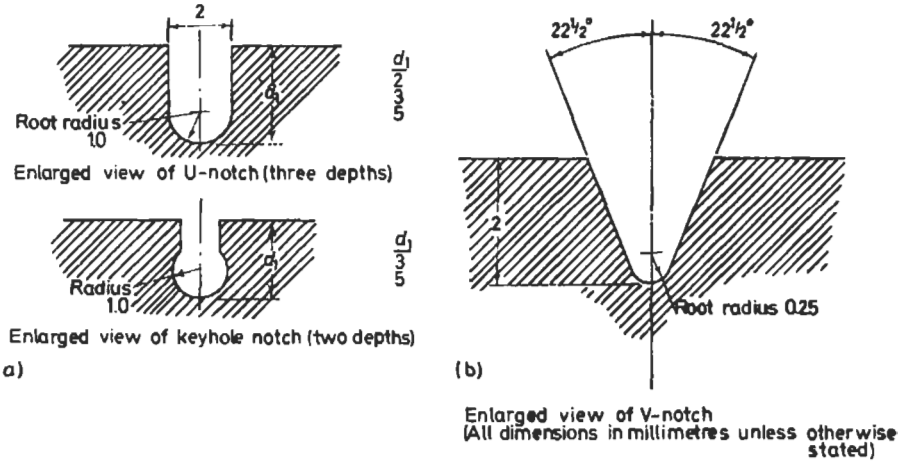


Figure 21.2 *Standard notch profiles for impact test pieces–see Table 21.15 and 21.16*

21.3.2 Charpy test

The test consists of measuring the energy absorbed in breaking by one blow from a pendulum a test piece notched in the middle and supported at each end.

TEST PIECES

The standard test piece has a 10 mm square cross-section with one of the three notch profiles shown in Figure 21.2. The test piece dimensions are shown in Table 21.16 Sub-standard test pieces are used where material thicknesses do not permit full-size specimens. It should be noted that the values obtained from subsidiary specimens cannot be compared with full-size specimens nor can the values obtained from different notches be compared.

PRESENTATION OF RESULTS

The report of the tests should include the following information:
Type of test: Charpy V or U notch; striking energy of the machine; size of test piece if sub-standard.
Nominal depth of notch and form ('U' or 'keyhole').
The energy absorbed (J) and the test temperature:

e.g. C160V: x J at y °C

† BS 131:Part 2:1972 uses SI units with 1 J ≈ 4/3 ft lbf for striking energies (1 ft lbf = 1.35582 J).

An energy of x J was recorded from a Charpy V notch specimen tested at y °C with a striking energy of 160 J:

e.g. C320U2: x J at y °C

In this case the specimen was a Charpy with a U notch 2 mm deep and the striking energy was 320 J.

Table 21.16 DIMENSIONS OF CHARPY IMPACT TEST PIECES—BRITISH STANDARDS BS 131:PART 2:1972; BS 131:PART 3:1972 (1982); AMERICAN STANDARD ASTM E23-86

	Nominal dimension	
Item	mm	inch *equivalent*
Length	55	2.165
Width standard test piece	10	0.394
subsidiary test piece[1]	7.5	0.295
subsidiary test piece	5.0	0.197
subsidiary test piece	2.5	0.098
Thickness	10	0.394
Root radius of V notch	0.25	0.010
Depth below V notch	8	0.315
Root radius of U notch	1	0.039
Depth below U notch	8 (2 mm notch)[2, 3]	0.315
	7 (3 mm notch)[2, 3]	0.276
	5 (5 mm notch)	0.197
Distance of notch from one end of test piece	27.5	1.083
Angle between plane of symmetry of notch and longitudinal axis of test piece	90°	
Angle of V notch	45°	

Notes: (1) Additional subsidiary test pieces are permitted by ASTM E23-86 as follows: 5 mm thick with 4 mm depth below the notch and 5, 10 or 20 mm width and 3 mm thick with 0.094 in (2.39 mm) depth below notch and 10 mm width.
(2) Not specified in ASTM E23-86.
(3) The 2, 3 and 5 mm notches are sometimes referred to as 'Mesnager', 'DVM' and 'Charpy', respectively.

21.4 Fracture toughness testing

21.4.1 Plane strain (K_{Ic})

Standards: British BS 5447:1977 (1987)
American ASTM E399-83

The method involves the loading to failure in tension or three point bend of notched specimens which have been precracked by fatigue loading. The load versus displacement across the notch at the specimen edge is recorded autographically. The load corresponding to a 2% increment of crack extension is established by a specified deviation from the linear portion of the record. The fracture toughness, K_{Ic}, value is calculated from this load by equations which have been established on the basis of elastic stress analysis of the two specimen types.

Stress-intensity factor K_I: A measure of the stress-field intensity near the tip of a crack in a linear elastic body when deformed so that the crack faces are displaced apart, normal to the crack plane (Opening Mode or Mode I deformation). K_I is directly proportional to the applied load and depends on the specimen geometry.

Plain strain fracture toughness K_{Ic}: A material toughness property—the critical value of the stress intensity factor at which rapid propagation of a crack occurs during static loading.

TEST PIECES

The particular type of test piece used depends upon the form, the strength and the toughness of the material under test.

The basis of the test piece size requirements* is that both the crack length, a, and the thickness, B, shall be not less than $2.5[(K_{Ic})/(\sigma_Y)]^2$ where σ_Y is 0.2% proof stress of the material under the conditions of test, i.e. orientation, temperature and loading rate. In the first place, the test piece size has to be based on an approximate estimate of the K_{Ic} of the material, it is better to overestimate the K_{Ic} value initially and subsequently use a more conservative test piece if possible, on the basis of the first test results. Alternatively, the ratio of yield strength to Young's modulus given in Table 21.17 can be used a a guide for selecting the initial test piece size.

Table 21.17 RECOMMENDED THICKNESS AND CRACK LENGTH FOR FRACTURE TOUGHNESS TEST PIECES

	Minimum recommended thickness and crack length	
σ_Y/E	mm	in
up to 0.005 0	100	4.0
0.005 0–0.005 7	75	3.0
0.005 7–0.006 2	63	2.5
0.006 2–0.006 5	50	2.0
0.006 5–0.007 1	38	1.5
0.007 1–0.008 0	25	1.0
0.008 0–0.009 5	13	0.5
0.009 5 or greater	6.5	0.25

If, however, it is not possible to produce a test piece having both crack length and thickness not less than 2.5 $[(K_{Ic})/(\sigma_Y)]^2$ then it is not possible to obtain a valid K_{Ic} determination according to the standard procedures. See Section 21.4.2 for an alternative measure of fracture toughness.

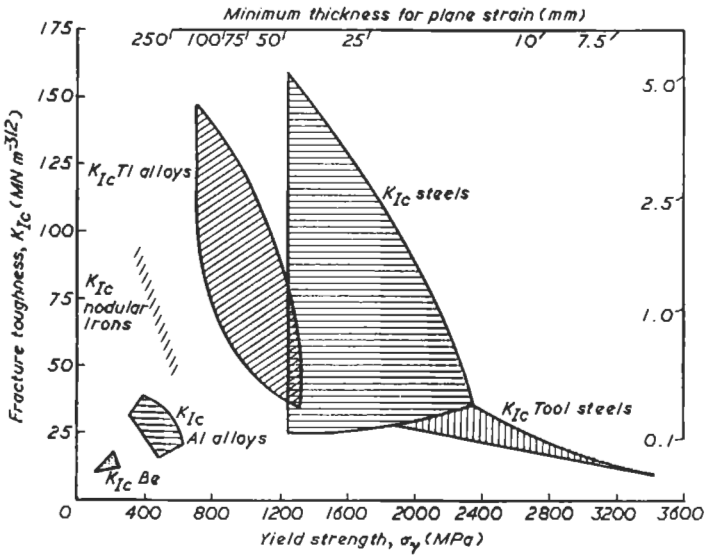
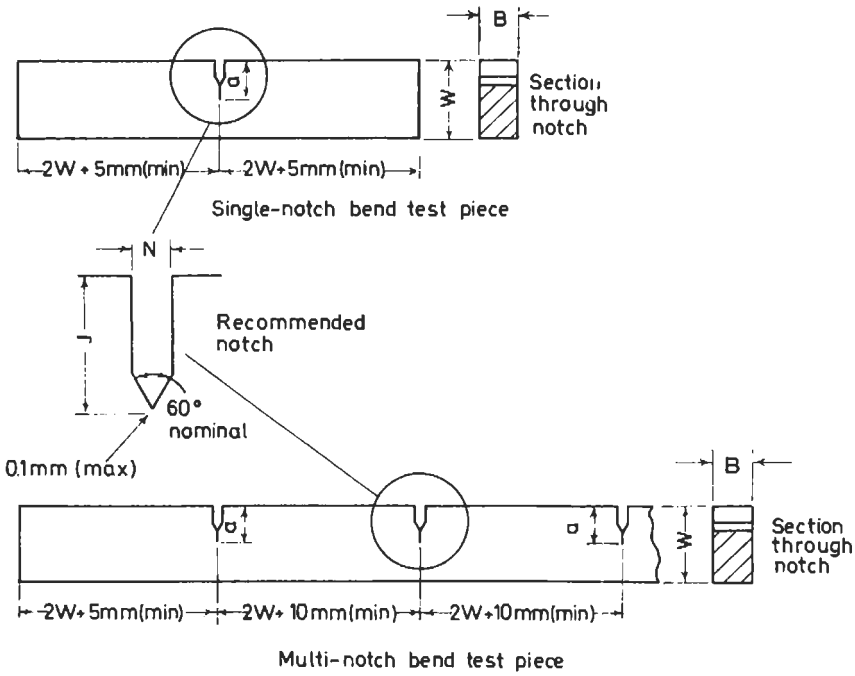


Figure 21.3 *Yield strength versus fracture toughness data for several alloy systems at 20 °C. The upper scale of the diagram indicates the minimum thickness requirement for a given strength and toughness by projection of the line joining the origin and data point. (Source: Fulmer Materials Optimizer, Fulmer Laboratories Ltd, Buckinghamshire, UK).*

*For graphical assessment see Figure 21.3.

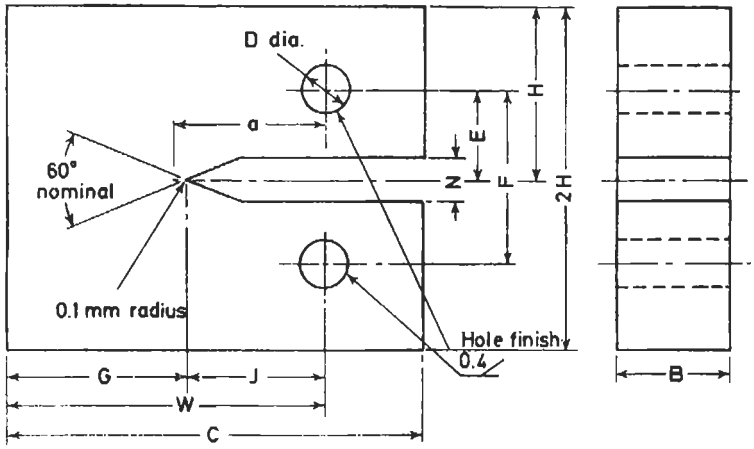


Test piece. Proportion, dimensions and limits

Width	$=W$
Thickness	$=B=\frac{1}{2}W$
Crack length	$a=0.45\ W–0.55\ W$
Notch length	$J=0.25\ W–0.45\ W$
i.e. 0.25 W when	$W=13$ mm
0.45 W when	$W=150$ mm

Notch width not greater than $\frac{1}{16}W$ (when W is equal to or less than 25 mm N may be up to $1\frac{1}{2}$ mm). Faces parallel and perpendicular to 0.02 mm taper per 10 mm run.

Figure 21.4 *Standard bend test piece from BS 5447: 1977 (1987)*



Proportional dimensions and limits

Net width	W
Crack length	$a = 0.45\ W$–$0.55\ W$
Thickness	$B = 0.5\ W$
Total width	$C = 1.25\ W$
Hole diameter	$D = 0.25\ W$
Half hole centres	$E = 0.275\ W$
Hole centres	$F = 0.55\ W$
	G = not less than $0.55\ W$
	$H = 0.6\ W$
	J = see Figure 21.4
Notch width	N = not greater than $\frac{1}{18}\ W$

When W is equal to or less than 25 mm N may be up to $1\frac{1}{2}$ mm. Surfaces parallel and perpendicular as applicable to 0.02 mm taper/per 10 mm run.

	Size	*B*	*W*	*C*	*a max.*	*N max.*	*E*	*F*	*H*	*D*	*G min.*
	13	13	26	32.5	14.5	1.5	7.2	14.3	15.6	6.5	14.3
	25	25	50	62.5	27.5	3.1	13.8	27.5	30	12.5	27.5
Hence:	50	50	100	125	55	6.3	27.5	55	60	25	55
	75	75	150	188.5	82.5	9.4	41.3	82.5	90	37.5	82.5
	100	100	200	250	110	12.5	55	110	120	50	110

Finish to be 0.8 unless otherwise specified.
The dimensions given above are for a recommended series of test piece sizes.

Figure 21.5 *Standard tension test piece from BS 5447: 1977 (1987)*

CALCULATION AND INTERPRETATION OF RESULTS

Unlike most other forms of mechanical test, plane strain fracture toughness testing has to be completed and the results analysed before it is known if a valid measurement has been made. It is necessary to calculate a provisional result K_Q, which involves a construction from the test record, and then to determine whether this result is consistent with the test piece size requirements for the proof stress of the material.

OFFSET PROCEDURE

A secant line through the origin is drawn with a slope 5% less than the slope of the tangent to the initial linear part of the record. The force P_Q is defined as the intersection of the secant line with the test record or any higher recorded value of force preceding the intersection.

CALCULATION OF K_Q

K_Q is calculated from P_Q using one of the following relationships.

For the bend test

$$K_Q = \frac{3\,P_Q L}{BW^{3/2}}\left[1.93\left(\frac{a}{W}\right)^{1/2} - 3.07\left(\frac{a}{W}\right)^{3/2} + 14.53\left(\frac{a}{W}\right)^{5/2} - 25.11\left(\frac{a}{W}\right)^{7/2} + 25.80\left(\frac{a}{W}\right)^{9/2}\right]$$

However, $L = 2W$, hence $K_Q = P_Q Y_1 / BW^{1/2}$

Values for Y_1 for specific values of a/W are given in Table 21.18.

For tension test piece

$$K_Q = \frac{P_Q}{BW^{1/2}}\left[29.6\left(\frac{a}{W}\right)^{1/2} - 185.5\left(\frac{a}{W}\right)^{3/2} + 655.7\left(\frac{a}{W}\right)^{5/2} - 1017\left(\frac{a}{W}\right)^{7/2} + 638.9\left(\frac{a}{W}\right)^{9/2}\right]$$

Hence $K_Q = \dfrac{P_Q Y_2}{BW^{1/2}}$

Values of Y_2 for specific values of a/W are given in Table 21.19.

CALCULATION OF K_{Ic}

The factor 2.5 $[(K_Q)/(\sigma_Y)]^2$ shall be calculated and if this is less than both the thickness and the crack length of the test piece then K_Q is equal to K_{Ic}. Otherwise, it is necessary to use a larger test piece to determine K_{Ic}, such that both thickness and crack length are not less than 2.5 $[(K_{Ic})/(\sigma_Y)]^2$. The new dimensions can be estimated on the basis of K_Q.

Table 21.18 VALUES OF Y_1 AGAINST a/W FOR BEND TEST PIECE THREE-POINT LOADED OVERALL SPAN TO TEST PIECE WIDTH RATIO 4:1

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
	Y_1 *Stress intensity coefficient*									
0.450	9.10	9.13	9.15	9.18	9.21	9.23	9.26	9.29	9.32	9.35
0.460	9.37	9.40	9.43	9.46	9.49	9.52	9.54	9.57	9.60	9.63
0.470	9.66	9.69	9.72	9.75	9.78	9.81	9.84	9.87	9.90	9.93
0.480	9.96	9.99	10.03	10.06	10.09	10.12	10.15	10.18	10.21	10.25
0.490	10.28	10.31	10.34	10.38	10.41	10.44	10.48	10.51	10.54	10.58
0.500	10.61	10.65	10.68	10.71	10.75	10.78	10.82	10.85	10.89	10.93
0.510	10.96	11.00	11.03	11.07	11.11	11.14	11.18	11.22	11.25	11.29
0.520	11.33	11.37	11.40	11.44	11.48	11.52	11.56	11.60	11.64	11.67
0.530	11.71	11.75	11.79	11.83	11.87	11.91	11.96	12.00	12.04	12.08
0.540	12.12	12.16	12.20	12.25	12.30	12.33	12.37	12.42	12.46	12.50
0.550	12.55									

Table 21.19 VALUES OF Y_2 AGAINST a/W FOR TENSION TEST PIECE

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
	Y_2 Stress intensity coefficient									
0.450	8.34	8.36	8.38	8.41	8.43	8.45	8.47	8.50	8.52	8.54
0.460	8.57	8.59	8.61	8.64	8.66	8.69	8.71	8.73	8.76	8.78
0.470	8.81	8.83	8.86	8.88	8.91	8.93	8.96	8.98	9.01	9.03
0.480	9.06	9.09	9.11	9.14	9.16	9.19	9.22	9.24	9.27	9.30
0.490	9.32	9.35	9.38	9.41	9.43	9.46	9.49	9.52	9.55	9.57
0.500	9.60	9.63	9.66	9.69	9.72	9.75	9.78	9.81	9.84	9.87
0.510	9.90	9.93	9.96	9.99	10.02	10.05	10.08	10.11	10.15	10.18
0.520	10.21	10.24	10.27	10.31	10.34	10.37	10.40	10.44	10.47	10.50
0.530	10.54	10.57	10.61	10.64	10.68	10.71	10.75	10.78	10.82	10.85
0.540	10.89	10.92	10.96	11.00	11.03	11.07	11.11	11.15	11.18	11.22
0.550	11.26									

RECORDING OF TEST RESULTS

The following data are usually recorded for each test:

1. Thickness: B in metres.
2. Width: W in metres.
3. Half loading span: L in metres for bend test only.
4. Fatigue precracking.
 (a) The fatigue stress intensity, K_f, during the last 1.25 mm (or 2.5% W whichever is the greater) increment of crack growth. This stress intensity should not exceed 0.7 K_Q.
 (b) The maximum fatigue stress intensity, used to initiate the crack. This stress intensity should not exceed 0.75 K_Q.
 (c) Temperature of the test piece during precracking. When fatigue cracking is conducted at a temperature T_1 and the testing carried out at a temperature T_2, K_f during the final stages of cracking should be less than $[(2\sigma_{Y1})/(3\sigma_{Y2})]\,K_{1C}$ where σ_{Y1} and σ_{Y2} are the proof stresses at the temperatures T_1 and T_2.
 (d) The R ratio, i.e. the ratio of the minimum to the maximum fatigue load. It is recommended that R should not be greater than 0.1.
5. Crack length: a in metres. The crack length is measured from the fractured test piece at 25%, 50% and 75% of the specimen thickness and the average of these three values quoted. The crack is regarded as unsatisfactory if any of these measurements differ by more than 2.5% W or if any two possible crack length measurements differ by more than 5% W.
6. Test temperature.
7. Environment.
8. Loading rate in terms of $\dot{K}$ (change in stress intensity factor per unit time) if outside the standard range of 0.5–2.5 MN m$^{-3/2}$ s^{-1}.
9. 0.2% proof stress in MPa.
10. K_{Ic}: in MN m$^{-3/2}$. Note $K_{Ic} = K_Q$ if the size requirements are satisfied.

21.4.2 Plane stress COD

Standards: BS 5762:1979 (1986)

This standard extends the fracture toughness test beyond the linear elastic behaviour in the plane strain regime, covered by BS 5447 and E399, into the elastic–plastic regime of plane stress. The crack opening displacement, COD, at the crack tip is determined as a measure of the stress intensity.

This test method is used for full thickness test pieces of material not thick enough to give valid K_{Ic} values, but which, nevertheless, fail by crack propagation before general yield. The critical COD is not a material property; it is only valid for the thickness of material under the conditions of the test. See Figures 21.6 and 21.7.

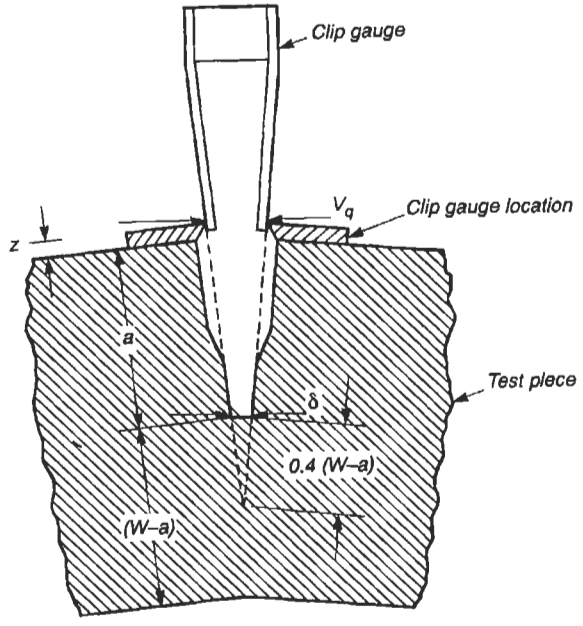


Figure 21.6 *Schematic representation of the method for deriving the crack opening displacement from clip gauge displacement.*

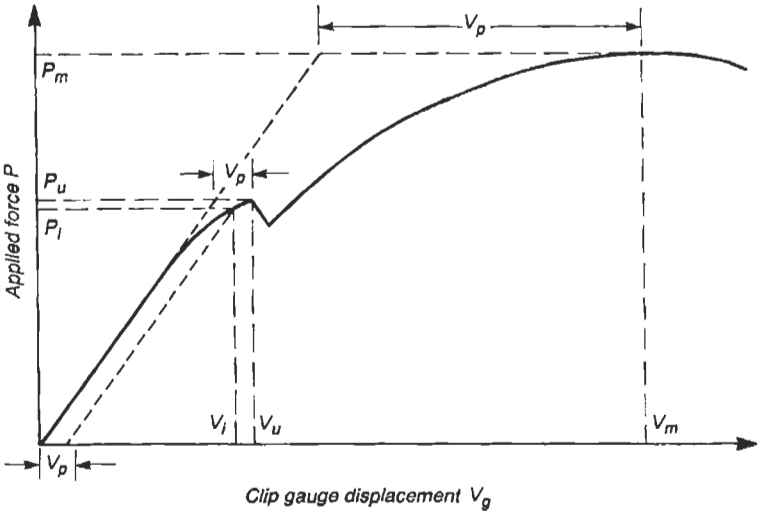


Figure 21.7 *Schematic force–displacement record for COD test showing the critical values at the points* (P_i, V_i), (P_u, V_u) *and* (P_m, V_m) *with corresponding plastic components,* V_p *of* V_q.

TEST PIECES

Bend test pieces of full thickness to BS 5447 with a relaxation of the crack length requirement so that $a = 0.15W$ to $0.7W$. See Figure 21.4.

CALCULATION AND INTERPRETATION OF RESULTS

Symbols:

P_i = The applied force at which slow crack growth starts.
P_u = The applied force at either
(a) unstable fracture, or
(b) the onset of arrested brittle crack propagation, preceded by slow crack growth.
P_m = The applied force at the maximum force plateau.
V_g = Clip gauge displacement.
V_i = Value at V_g at P_i.
V_u = Value of V_g at P_u.
V_m = Value of V_g at first attainment of the force plateau.
V_p = The plastic component of V_g determined from the force–displacement record as the offset from the initial elastic load line (the procedure employed in proof stress determinations).
δ = The crack tip opening displacement.
z = The distance of the clip gauge location from the test piece surface.
ν = Poisson's ratio,
K = The stress intensity calculated from the bend test relation for K_Q in BS 5447, using corresponding values of P_i, P_u or P_m. (*See* page **21**–16.)

The crack opening displacement is calculated from the clip gauge displacement as

$$\delta = \frac{K^2(1-\nu^2)}{2\sigma_Y E} + \frac{0.4(W-a)V}{0.4W+0.6a+z}$$

RECORDING OF TEST RESULTS

The data recorded for BS 5447 are required by BS 5762 with the following additions:

(1) the force displacement record,
(2) the plastic component of the clip gauge displacement V_i, V_u or V_m (mm),
(3) the corresponding force P_i, P_u or P_m (N),
(4) distance of the clip gauge location z (mm) from the surface of the test piece, and
(5) the critical COD δ_i, δ_u or δ_m (mm) calculated from the equation above using corresponding values at V_i, V_u or V_m.

22 Mechanical properties of metals and alloys

The following tables summarize the mechanical properties of the more important industrial metals and alloys.

In the tables of tensile properties at normal temperatures the nominal composition of the alloys is given, followed by the appropriate British and other specification numbers. Most specifications permit considerable latitude in both composition and properties, but the data given in these tables represent typical average values which would be expected from materials of the nominal composition quoted, unless otherwise stated. For design purposes it is essential to consult the appropriate specifications to obtain minimum and maximum values and special conditions where these apply.

The data in the tables referring to properties at elevated and at sub-normal temperatures, and for creep, fatigue and impact strength have been obtained from a more limited number of tests and sometimes from a single example. In these cases the data refer to the particular specimens tested and cannot be relied upon as so generally applicable to other samples of material of the same nominal composition.

22.1 Mechanical properties of aluminium and aluminium alloys

The compositional specifications for wrought aluminium alloys are now internationally agreed throughout Europe, Australia, Japan and the USA. The system involves a four-digit description of the alloy and is now specified in the UK as BS EN 573, 1995. Registration of wrought alloys is administered by the Aluminum Association in Washington, DC. International agreement on temper designations has been achieved, and the standards agreed for the European Union, the Euro-Norms, are replacing the former British Standards. Thus BS EN 515. 1995 specifies in more detail the temper designations to be used for wrought alloys in the UK. At present, there is no Euro-Norm for cast alloys and the old temper designations are still used for cast alloys.

In the following tables the four-digit system is used, wherever possible, for wrought materials.

22.1.1 Alloy designation system for wrought aluminium

The first of the four digits in the designation indicates the alloy group according to the major alloying elements, as follows: 1XXX – aluminium of 99.0% minimum purity and higher; 2XXX – copper; 3XXX – manganese; 4XXX – silicon; 5XXX – magnesium; 6XXX – magnesium and silicon; 7XXX – zinc; 8XXX – other element, incl. lithium; 9XXX – unused; 1XXX Group – In this group the last two digits indicate the minimum aluminium percentage. Thus 1099 indicates aluminium with a minimum purity of 99.99%. The second digit indicates modifications in impurity or alloying element limits. 0 signifies unalloyed aluminium and integers 1 to 9 are allocated to specific additions; 2XXX-8XXX Groups – In these groups the last two digits are simply used to identify the different alloys in the groups and have no special significance. The second digit indicates alloy modifications, zero being allotted to the original alloy.

National variations of existing compositions are indicated by a letter after the numerical designation, allotted in alphabetical sequence, starting with A for the first national variation registered.

The specifications and properties for Cast Aluminium Alloys are tabulated in Chapter 26 as Table 26.26.

22.1.2 Temper designation system for aluminium alloys

The following tables use the internationally agreed temper designations for wrought alloys, (BS EN 515. 1995) and the more frequently used ones are listed below. The old ones still used for existing BS specifications e.g. BS 1490. 1989 for castings are compared with the new ones at the end of this section.

Table 22.1

U.K.	*Meaning*
F	As manufactured or fabricated
H111	Fully soft annealed condition
Strain-hardened alloys	
H	Strain hardened non-heat-treatable material
H1x	Strain hardened only
H2x	Strain hardened only and partially annealed to achieve required temper
H3x	Strain hardened only and stabilized by low temperature heat treatment to achieve required temper
H12,H22,H32	Quarter hard, equivalent to about 20–25% cold reduction
H14,H24,H34	Half hard, equivalent to about 35% cold reduction
H16,H26,H36	Three-quarter hard, equivalent to 50–55% cold reduction
H18,H28,H38	Fully hard, equivalent to about 75% cold reduction
Heat-treatable alloys	
T1	Cooled from an Elevated Temperature Shaping Process and aged naturally to a substantially stable condition
T2	Cooled from an Elevated Temperature Shaping Process, cold worked and aged naturally to a substantially stable condition
T3	Solution heat-treated, cold worked and aged naturally to a substantially stable condition
T4	Solution heat-treated and aged naturally to a substantially stable condition
T5	Cooled from an Elevated Temperature Shaping Process and then artificially aged
T6	Solution heat-treated and then artificially aged
T7	Solution heat-treated and then stabllized (over-aged)
T8	Solution heat-treated, cold worked and then artificially aged
T9	Solution heat-treated, artificially aged and then cold worked
T10	Cooled from an Elevated Temperature Shaping Process, artificially aged and then cold worked

A large number of variants in these tempers has been introduced by adding additional digits to the above designations. For example, the addition of the digit 5 after T1-9 signifies that a stress relieving treatment by stretching has been applied after solution heat-treatment.

A full list is given in BS EN 515. 1995 but some of the more common ones used in the following tables are given below.

T351 Solution heat-treated, stress-relieved by stretching a controlled amount (usually 1–3% permanent set) and then naturally aged. There is no further straightening after stretching. This applies to sheet, plate, rolled rod and bar and ring forging.

T3510 The same as T351 but applied to extruded rod, bar, shapes and tubes.

T3511 As T3510, except that minor straightening is allowed to meet tolerances.

T352 Solution heat-treated, stress-relieved by compressing (1–5% permanent set) and then naturally aged.

T651 Solution heat-treated, stress-relieved by stretching a controlled amount (usually 1–3% permanent set) and then artificially aged. There is no further straightening after stretching. This applies to sheet, plate, rolled rod and bar and ring forging.

T6510 The same as T651 but applied to extruded rod, bar, shapes and tubes.

T6511 As T6510, except that minor straightening is allowed to meet tolerances.

T73 Solution heat-treated and then artificially overaged to improve corrosion resistance.

T7651 Solution heat-treated, stress-relieved by stretching a controlled amount (Again about 1–3% permanent set) and then artificially over-aged in order to obtain a good resistance to exfoliation corrosion. There is no further straightening after stretching. This applies to sheet, plate, rolled rod and bar and to ring forging.

T76510 As T7651 but applied to extruded rod, bar, shapes and tubes.

T76511 As T7510, except that minor straightening is allowed to meet to tolerances.

In some specifications, the old system is still being applied. The equivalents between old and new are as follows TH7 is as TH and then stabilised; F/M is as manufactured or fabricated.

BS EN 515	BS1470/90	Pre-1969 BS
	F	M
	0	0
H111	0	0
T3	TD	WD
T4	TB	W
T5	TE	P
T6	TF	WP
T8	TH	WDP

Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. %* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact engery* J	*Fracture toughness* (MPa $m^{1/2}$)	*Remarks*
1199	Al 99.99	Sheet	H111	20	55	55	50	15	–	–	–	Highest quality
			H14	60	85	20	60	23	–	–	–	reflectors
			H18	85	110	12	70	28	–	–	–	
1080A	Al 99.8	Sheet	H111	25	70	50	60	19	–	–	–	Domestic trim,
			H14	95	100	17	70	29	–	–	–	chemical plant
			H18	125	135	11	70	29	–	–	–	
		Wire	H111	–	70	–	60	19	–	–	–	
			H14	90	105	–	70	30	–	–	–	
			H18	110–140	130–160	–	–	35–41	–	–	–	
1050A	Al 99.5	Sheet	H111	35	80	47	65	21	–	–	–	General purpose
			H14	105	110	15	75	30	–	–	–	formable alloy
			H18	130	145	10	85	40	–	–	–	
		Bars and sections as extruded		50	75	38	65	22	–	–	–	
		Rivet stock	H15	125	140	–	–	–	–	–	–	
		Tubes	H111	–	75	–	65	21	–	–	–	
			H18 < 75 mm	120	125	–	75	–	–	–	–	
			H18 > 75 mm	110	115	–	70	–	–	–	–	
		Wire	H111	42	75	–	65	21	–	–	–	
			H14	100	115	–	75	30	–	–	–	
			H18	115–170	140–195	–	–	38–48	–	–	–	
1350	Al 99.5	Wire	H111	28	83	–	55	–	–	–	–	Electrical
			H14	97	110	–	69	–	–	–	–	conductors
			H18	165	186	–	103	–	48	–	–	
1200	Al 99.0	Sheet	H111	35	90	43	70	22	35	27	–	
			H13	95	105	20	75	31	40	–	–	General purpose,
			H14	115	120	12	80	35	50	31	–	slightly higher strength
			H16	125	135	11	90	38	60	–	–	than 105A
			H18	145	160	9	95	42	60	26	–	

continued overleaf

Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. %* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact engery* J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
		Bars and sections as extruded		40	85	38	70	23	45*	27		
		Tubes	H111	–	90	40	70	21	–	–	–	
			H > 75 mm	128	131	6	100	34	–	–	–	
			H < 75 mm	120	124	6	95	32	–	–	–	
2011	Cu 5.5	Extruded bar	T3 25 mm	295	340	14	240	95	–	–	–	Free machining alloy
	Bi 0.5		T6 50–75 mm	260	370	16	240	100	–	–	–	
	Pb 0.5	Wire	T3 $\leq$ 10 mm	350	365	–	–	–	–	–	–	
2014	Cu 4.4	Plate	T451	290	425	22	260	108	140	–	–	Heavy duty
	Mg 0.7		T651	415	485	10	290	139	125	–	–	applications in trans-
	Si 0.8	Bar/tube	T6510	440	490	8	–	–	–	–	–	port and aerospace,
	Mn 0.75											e.g. large parts, wings
2014A	Cu 4.4	Sheet	T4	270	450	20	260	115	130*	–	–	Aircraft applications
	Mg 0.7		T6	430	480	10	295	135	130*	–	–	(cladding when used
	Si 0.8	Clad sheet	T4	250	425	22	250	–	95*	–	–	1070A)
	Mn 0.75		T6	385	440	10	260	–	95*	–	–	
		Bars and sections	T4	315	465	17	–	115	140	22	–	
			T6	465	500	10	–	135	124	8	–	
		Tubes	T4	310	425	12	–	115	–	–	–	
			T6	415	480	9	–	135	–	–	–	
		Wire	T4	340	445	15	–	115	–	–	–	
			T6	425	465	–	–	135	–	–	–	
		River stock	T4	340	450	–	–	–	–	–	–	
		Bolt and screw stock	T6	425	460	–	–	–	–	–	–	
2024	Cu 4.5	Plate	T3	345	485	18	285	120	140	–	–	Structural applications,
	Mg 1.5		T351	325	470	19	285	120	140	–	–	especially transport
	Mn 0.6											and aerospace

2024	Cu 4.5 Mg 1.5 Mn 0.6	Plate/sheet extrusions	H111 T4 T6	75 325 395	185 470 475	20 20 10	125 285 –	47 120 –	90 140 –	– – –	– – –	Aircraft structures
2117	Cu 2.5 Si 0.6 Mg 0.4	Sheet	T4	165	295	24	195	70	95	–	–	Vehicle body sheet
2090	Cu 2.7 Li 2.7 Zr 0.12	Plate Plate (12.5 mm)	T81 T81	517 535	550 565	8 11	– –	– –	– –	– –	71 34	High strength, low density aero-alloy Ref (Glazer and Morris)
2091	Cu 2.1 Li 2.0 Mg 1.50 Zr 0.1	Plate (12 mm) Plate (40 mm) Extrusion (10 mm)	T8X51 T8X51 T851	310 310 505	420 430 580	14 6 7	– – –	– – –	– – –	– – –	– – 35	Medium strength, low density aero-alloy in damage-tolerant temper
		Extrusion (30 mm)	T851	465	520	11	–	–	–	–	35	
		Plate (12 mm)	T851	460	525	10	–	–	–	–	43	Medium strength, low
		Plate (38 mm)	T851	430	495	8	–	–	–	–	38	density aero-alloy
		Sheet	T8	390	495	10	–	–	–	–	38	Medium strength, low density aero-alloy
2219	Cu 6 Mn 0.3 V 0.1	Plate/sheet/ forgings	H111 T4 T6	75 185 290	170 360 415	18 20 10	– – –	– – –	– – 105	– – –	– – –	Weldable, creep resistant, high- temperature aerospace applications
2004	Cu 6 Zr 0.4	Sheet	H111 T6	150 300	230 420	15 12	– –	– –	100* 150*	– –	– –	Superplastically deformable sheet
2031	Cu 2.3 Ni 1.0 Mg 0.9 Si 0.9 Fe 0.9	Forgings	T4 T6	235 340	355 420	22 15	201 201	95 95	– –	– –	– –	Aero-engines, missile fins
2618A	Cu 2.0 Mg 1.5 Si 0.9 Fe 0.9 Ni 1.0	Forgings	H111 T6	70 330	170 430	20 8	– 295	45 130	85* 170*	– –	– –	Aircraft engines

continued overleaf

Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. %* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact engery* J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
3103	Mn 1.25	Sheet	H111	65	110	40	80	30	50	34	–	General purpose, holloware, building sheet
			H12	125	130	17	90	40	55	–	–	
			H14	140	155	11	95	44	60	29	–	
			H16	160	180	8	105	47	70	–	–	
			H18	185	200	7	110	51	70	20	–	
		Wire	H111	60	115	–	–	30	–	–	–	
			H14	135	155	–	–	45	–	–	–	
			H18	170–200	205–245	–	–	55–65	–	–	–	
3105	Mn 0.35 Mg 0.6	Sheet	H111	55	115	24	85	–	–	–	–	Building cladding sheet
			H14	150	170	5	105	–	–	–	–	
			H18	195	215	3	115	–	–	–	–	
3004	Mn 1.2 Mg 1.0	Sheet	H111	70	180	20	110	45	95	–	–	Sheet metal work, storage tanks
			H14	200	240	9	125	63	105	–	–	
			H18	250	285	5	145	77	110	–	–	
3008	Mn 1.6 Fe 0.7 Zr 0.3	Sheet	H111	50	120	23	–	–	–	–	–	Thermally reistant alloy. Vitreous enamelling
			H18	270	280	4	–	–	–	–	–	
3003 clad with 4343	Mn 1.2 Si 7.5	Sheet	H111	40	110	30	75	–	–	–	–	Flux brazing sheet
			H12	125	130	10	85	–	–	–	–	
			H14	145	150	8	95	–	–	–	–	
			H16	170	175	5	105	–	–	–	–	
3003 clad with 4004	Mn 1.2 Si 1.0 Mg 1.5	Sheet	Physical properties		as for 3003 clad with 4343			–	–	–	–	Vacuum brazing sheet
4032	Si 12.0 Cu 1.0 Mg 1.0 Ni 1.0	Forgings	T6	240	325	5	–	115	110	–	–	Pistons

4043A	Si 5.0	Rolled wire		75	130	20	–	–	–	–	–	Welding filler wire
4047A	Si 12.0	Wire	F	189	225	8	–	–		–	–	Brazing rod
5657	Mg 0.8	Sheet	H111	40	110	25	75	28	–	–	–	High base purity,
			H14	140	160	12	95	40	–	–	–	bright trim alloy
			H18	165	195	7	105	50	–	–	–	
5005	Mg 0.8	Sheet	H111	40	125	25	75	28	–	–	–	Architectural trim,
			H14	150	160	6	95	–	–	–	–	commercial vehicle
			H18	195	200	4	110	–	–	–	–	trim
5251	Mg 2.25	Sheet	H111	95	185	22	125	45	110	50	–	Sheet metal work
	Mn 0.25		H14	230	245	7	145	70	125	29	–	
			H18	275	285	2	175	80	140	–	–	
5251	Mg 2.0	Bar	F	60	170	16	–	–	–	–	–	Marine and transport
	Mn 0.3	Sheet	H111	60	180	20	125	47	92	–	–	applications; good
			H22	130	220	8	132	65	124	–	–	workability combined
			H24	175	250	5	139	74	–	–	–	with good corrosion
			H28	215	270	4	–	–	–	–	–	resistance and high fatigue resistance
		Bars and sections as extruded (F)		95	185	20	125	45	95*	49	–	
		Tubes	H111	100	200	20	–	–	–	–	–	
			H14	230	250	6	–	–	–	–	–	
			H18	255	270	5	–	–	–	–	–	
		Wire	H111	95	200	–	–	48	–	–	–	
			H18	260–290	280–310	–	–	75–85	–	–	–	
5154A	Mg 3.5	Sheet	H111	125	240	24	155	55	115	–	–	Welded structures,
	Mn 0.5		H22	245	295	10	175	80	125	–	–	storage tanks, salt
			H24	275	310	9	175	95	130	–	–	water service
		Bars and sections as extruded (F)		125	230	25	145	55	140*	48	–	
		Tubes	H111	125	225	20	–	55	–	–	–	
			H14	220	280	7	–	–	–	–	–	
		Wire	H111	125	240	–	–	55	–	–	–	
			H14	265	295	–	–	90	–	–	–	
			H18	310	355	–	–	100	–	–	–	
		Rivet stock	H111	125	250	–	–	–	–	–	–	
			H12	–	290	–	–	–	–	–	–	

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Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. %* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact engery* J	*Fracture toughness* (MPa m$^{1/2}$)	*Remarks*
5454	Mg 2.7 Mn 0.75 Cr 0.12	Sheet	H111 H22 H24	105 200 225	250 277 297	22 7 5	159 165 179	65 77 85	115 125 130	– – –	– – –	Higher strength alloy for marine and transport, pressure vessels and welded structures
5083	Mg 4.5 Mn 0.7 Cr 0.15	Sheet Bars and sections as extruded (F)	H111 H24	170 290 180	310 370 315	21 9 19	170 210 180	72 110 77	– – –	– – –	– – –	Marine applications, cryogenics, welded pressure vessels.
5083	Mg 4.5 Mn 4.5 Cr 0.15	Tube	H111 H14	180 300	320 375	20 7	– –	77 –	– –	– –	– –	
5556A	Mg 5	Wire	H14	250	330	12	–	–	–	–	–	Weld filler wire
5056A	Mg 5.0 Mn 0.5	Wire	H111 H14 H18	140 300 340–400	300 340 400–450	– – –	– – –	65 95 110–120	– – –	– – –	– – –	Rivets, bolts, screws
		Rivet stock	H111 H12	140 –	300 350	– –	– –	65 –	– –	– –	– –	
		Bolt and screw stock	H14	300	340	–	–	–	–	–	–	
6060	Mg 0.5 Si 0.4	Bar	T4 T5 T6	90 130 190	150 175 220	20 13 13	– – –	– – –	– – –	– – –	– – –	Medium strength extrusion alloy for doors, windows, pipes, architectural use; weldable and corrosion-resistant

6063	Mg 0.5 Si 0.5	Bars, sections and forgings	F	85	155	30	100	35	–	–	–	Architectural extrusions (fast extruding)
			T4	115	180	30	130	52	60	43	–	
			T6	210	245	20	160	75	70	31	–	
		Wire	H111	–	115	–	–	–	–	–	–	
			T4	115	180	–	–	50	–	–	–	
			T6	195	230	–	–	70	–	–	–	
6063A	Mg 1.0 Si 0.5	Bar	T6510	280	310	22	129	50	79	–	–	Transport, windows, furniture, doors and architectural uses, pipes (irrigation)
			T5	160	200	12	117	65	69	–	–	
			T6	210	240	12	152	78	85	–	–	
6061	Mg 1.0 Si 0.6 Cr 0.25 Cu 0.2	Bars and sections	T4	145	230	20	160	60	–	34	–	Intermediate strength extrusion alloy
			T6	280	310	13	200	90	–	27	–	
		Wire	T8 ≤ 6 mm	310–400	385–430	–	–	–	–	–	–	
			T8 (6–10 mm)	295–385	380–415	–	–	–	–	–	–	
		Bar	T6510	280	310	13	205	100	95	–	–	
		Bolt and screw stock	T8	290	340	–	–	–	–	–	–	
6082	Mg 1.0 Si 1.0 Mn 0.7	Bar/extrusion	T5	260	300	15	185	85	–	–	–	
			T6510	285	315	11	–	–	–	–	–	
		Plate	T451	150	240	19	–	68	–	–	–	
			T651	289	315	12	–	104	–	–	–	
	Mn 0.5		T6	285	315	12	205	100	–	–	–	
		Bars, sections and forgoings	T4	160	240	25	180	65	–	41	–	
			T6	285	310	13	215	100	–	34	–	
		Tubes	T4	160	245	20	–	65	–	–	–	
			T6	285	325	10	–	95	–	–	–	
6463	Mg 0.55 Si 0.4	Bar	T4	130	180	16	–	55	70	–	–	
			T6	215	240	12	150	79	70	–	–	
6009	Si 0.8 Mg 0.6 Mn 0.5 Cu 0.4	Sheet	T4	130	235	24	205	60	97	–	–	Vehicle body sheet
			T6	325	345	12	150	–	115	–	–	

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Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Wrought Alloys

Specification	*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong. %* on 50 mm ($\geq$2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact engery* J	*Fracture toughness* (MPa $m^{1/2}$)	*Remarks*
7020	Zn 4.5 Mg 1.2 Zr 0.15	Bars and sections	T4 T6	225 310	340 370	18 15	– –	100 126	– –	– –	– –	Transportable bridging
7075	Zn 5.6 Mg 2.5 Cu 1.6 Cr 0.25	Sheet/plate/ forgings/ extrusion	H111 T4 T73	105 505 435	230 570 505	17 11 13	150 330 –	60 150 –	– 160 –	– 7 –	– – –	Aircraft structures
7050	Zn 6.2 Mg 2.2 Cu 2.3 Zr 0.12	Thick section plate/ forgings	T736	455	515	11	–	–	220	–	–	Low quench sensitivity, high stress corrosion resistance. Aircraft structures
7475	Zn 5.7 Mg 2.2 Cu 1.5 Cr 0.2	Sheet/plate/ forgings	T61 T7351	525 –	460 –	12 –	– 270	– –	– 220	– –	– –	High base purity. High fracture toughness. Aircraft structures
7016	Zn 4.5 Mg 1.1 Cu 0.75	Extrusions	T6	315	360	12	–	–	–	–	–	Bright anodized vehicle bumpers
7021	Zn 5.5 Mg 1.5 Cu 0.25 Zr 0.12	Extrusion	H111 T6	115 395	235 435	16 13	– –	– –	– –	– –	– –	Bumper backing bars
8079	Fe 0.7	Foil	H111 H18	35 160	95 175	26 2	– –	– –	– –	– –	– –	Domestic foil

8090	Li 2.5 Cu 1.3 Mg 0.95 Zr 0.1	Plate		483	518	4.3	–	–	–	–	42	As 2090 but lower density
		Plate (38/65 mm)	T8151	387	476	6.5	–	–	–	–	42.5	Under-aged, damage-tolerant condition
			T8771	483	518	4.3	–	–	–	–	42	Peak-aged, medium strength condition
		Sheet	T81	360	420	11	–	–	–	–	42	Under-aged, damage-tolerant condition with a recrystallized grain structure
			T6	373	472	5.7	–	–	–	–	–	
			T8	436	503	5	–	–	–	–	75	Peak-aged, medium strength condition
		Extrusion	T81551	440	510	4	–	–	–	–	45	Damage-tolerant condition
			T82551	460	515	4.2	–	–	–	–	39	Peak-aged, medium
		Extrusion (10 mm)	T851	515	580	5	–	–	–	–	30	strength condition
		Extrusion (30 mm)	T851	460	520	9	–	–	–	–	40	
		Plate (12 mm)	T851	455	500	7	–	–	–	–	33	
8090	Li 2.4 Cu 1.2 Mg 0.50 Zr 0.14	Forging	T651	468	517	7	–	–	–	–	28.1	Peak-aged (32 h at 170 °C. (Shrimpton)
			T651	400	453	7	–	–	–	–	36.7	Under-aged (20 h at 150 °C). (Shrimpton)
8090	Li 2.5 Cu 1.2 Mg 0.66 Zr 0.12	Forging		420	499	7.8	–	–	–	–	16.98	Soln. trt, 530 °C, WQ, aged 30 h at 170 °C
8091	Li 2.4 Cu 1.9 Mg 0.85 Zr 0.1		–	–	–	–	–	–	–	–	–	
	Li 2.4 Cu 2.0 Mg 0.70 Zr 0.08	Plate (40 mm)		460	–	–	–	164	–	–	–	Peak-aged (6% stretch, 32 h at 170 °C
				408	–	–	–	159	–	–	–	Peak aged (no stretch, 100 h at 170 °C)
				408	–	–	–	158	–	–	–	Duplex-aged (ditto, 24 h at RT, 48 h at 170 °C)
	Li 2.3 Cu 1.7 Mg 0.64 Zr 0.13	Forging	–	436	503	8.2	–	–	–	–	20.72	soln. trt. 530 °C, WQ, aged 20 h at 170 °C

continued overleaf

Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Cast Alloys

Specification		*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.%* on 50 mm (≥2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact energy* J	*Fracture toughness* (MPa $m^{1/2}$)	*Remarks*
Al	(LMO)	Al 99.0	Sand cast	F	30	80	30	55	25	30*	19	–	High conductivity,
			Chill cast	F	30	80	40	55	25	30*	19	–	high ductility
Al–Mg	(LM5)	Mg 5.0	Sand cast	F	100	160	6	–	60	45	8	–	Very high corrosion
		Mn 0.5	Chill cast	F	100	215	10	–	65	95	12	–	resistance
	(LM10)	Mg 10.0	Sand cast	T4	180	295	12	230	85	55	15	–	Strength + corrosion
			Chill cast	T4	190	340	18	230	95	–	–	–	resistance
Al–Si	(LM18)	Si 5.0	Sand cast	F	60	125	5	90	40	55	1.5	–	Intricate castings
			Chill cast	F	70	155	6	120	50	85	2.5	–	
	(LM6) (LM20)	Si 11.5	Sand cast	F	65	170	8	110	55	45*	4	–	Very similar alloys, excellent casting
	(LM6)		Chill cast	F	75	215	10	130	60	60*	9.5	–	characteristics and corrosion resistance. LM6 has slightly supperior corrosion resistance
Al–Si–Mg		Si 7	Sand cast	T6	195	240	3	–	–	56	–	–	Good strength in fairly
	(2L99)	Mg 0.4	Chill cast	T6	210	290	6	–	90	90	–	–	difficult castings. Cast vehicle wheels
Al–Cu–Si	(L154)	Cu 4.2	Sand cast	T4	170	225	8	–	–	–	–	–	Aircraft castings
		Si 1.2	Chill cast	T4	175	280	15	–	–	–	–	–	
	(L155)		Sand cast	T6	215	295	5	–	85	–	–	–	
			Chill cast	T6	215	320	10	–	90	–	–	–	
Al–Cu–Si	(LM24)	Cu 3.5	Chill cast	F	110	200	3	–	85	–	–	–	Excellent die casting
		Si 8.0	Die cast	F	150	320	2	–	85	–	–	–	alloy
	(LM4)	Cu 3.0	Sand cast	F	90	155	3	–	70	70*	0.7	–	General engineering,
		Si 5.0	Chill cast	F	100	170	3	–	80	75*	0.7	–	particularly sand and
			Sand cast	T6	230	260	1	–	105	–	–	–	permanent mould
			Chill cast	T6	260	330	3	–	110	–	–	–	castings

	(LM22)	Cu 3.0 Si 5.0 Mn 0.5	Chill cast	T4	115	260	9	–	75	–	4.5	–	Good combination of impact resistance and strength
	(LM2)	Cu 1.5 Si 10.0	Sand cast Chill cast	F F	85 95	140 185	1 2	– –	70 80	55 60	– –	– –	General purpose die casting alloy
Al–Cu–Mg	(LM12)	Cu 10.0 Mg 0.25	Chill cast Chill cast	F T6	155 285	185 310	1 –	– –	85 130	– 60	0.9 –	– –	Castings to withstand high hydraulic pressure
Al–Cu	(L119)	Cu 5.0 Ni 1.5	Sand cast	T6	200	225	2	–	90	–	–	–	Sand castings for elevated temperature service
Al–Zn–Mg	(DTT) 5008B	Zn 5.3 Mg 0.6 Cr 0.5	Sand cast	T4	–	220	5	–	–	–	–	–	Colour anodizing alloy
Al–Cu–Si–Zn	(LM27)	Cu 2.0 Si 7.0	Sand cast	F	85	155	2	–	75	–	–	–	Versatile general purpose alloy
			Chill cast	F	100	180	3	–	80	–	–	–	
Al–Si–Cu–Mg	(LM30)	Si 17.0 Cu 4.5 Mg 0.6	Chill cast Die cast Die cast	F F O	160 240 265	180 275 295	0.5 1 1	– – –	110 120 –	– – –	– – –	– – –	Die castings with high wear resistance, especially automobile cylinder blocks
	(LM16)	Si 5.0 Cu 1.0 Mg 0.5	Sand cast Chill cast	T4 T4	130 130	210 245	3 6	200 210	80 85	70 85	1.5 2.5	– –	Water-cooled cylinder heads and applications requiring leak-proof castings
			Sand cast Chill cast	T6 T6	245 275	255 310	1 2	215 225	100 110	60 70	1 1.5	– –	
Al–Si–Mg–Mn	(LM9)	Si 12.0 Mg 0.4 Mn 0.5	Sand cast Chill cast	T5 T5	120 160	185 255	2 2.5	120 160	70 80	55* 70*	1.5 2.5	– –	Fluidity, corrosion resistance and high strength. Extensive use for low-pressure castings
			Sand cast Chill cast	T6 T6	235 275	255 310	1 1	200 230	100 110	70* 85*	0.7 1.5	– –	

continued overleaf

Table 22.2 ALUMINIUM AND ALUMINIUM ALLOYS-MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Cast Alloys

Specification		*Nominal composition* %	*Form*	*Condition*	0.2% *Proof stress* MPa	*Tensile strength* MPa	*Elong.%* on 50 mm (≥2.6 mm) or $5.65\sqrt{S_0}$	*Shear strength* MPa	*Brinell hardness* ($P = 5D^2$)	*Fatigue strength (unnotched)* 500 MHz MPa	*Impact energy* J	*Fracture toughness* (MPa $m^{1/2}$)	*Remarks*
	(LM25)	Si 7.0	Sand cast	F	90	140	2.5	–	60	–	–	–	The most widely used
		Mg 0.3	Chill cast	F	90	180	4	–	60	–	–	–	general purpose, high-
			Sand cast	T5	135	165	1.5	–	75	55	–	–	strength casting alloy
			Chill cast	T5	165	220	2.5	–	85	–	–	–	
			Sand cast	T7	95	170	3	–	65	–	–	–	
			Chill cast	T7	100	230	8	–	70	75	–	–	
			Sand cast	T6	225	255	1	–	105	60	–	–	
			Chill cast	T6	240	310	3	–	105	95	–	–	
Al–Cu–Mg–Ni	(L35)	Cu 4.0	Sand cast	T6	220	235	1	–	115	80*	1.5	–	Highly stressed com-
(Y Alloy)		Mg 1.5	Chill cast	T6	240	290	2	–	115	110*	4.5	–	ponents operating at
		Ni 2.0											elevated temperatures
Al–Si–Cu–	(LM21)	Si 6.0	Sand cast	F	130	180	1	–	85	–	–	–	General engineering
Mg–Zn		Cu 4.0	Chill cast	F	130	200	2	–	90	–	–	–	applications,
		Mg 0.2											particular crankcases
		Zn 1.0											
Al–Si–Cu–		Si 23.0	Sand cast	T5	120	130	0.3	–	120	–	–	–	Pistons for high
Mg–Ni		Cu 1.0	Chill cast	T5	170	210	0.3	–	120	–	–	–	performance internal
													combustion engines
	(LM29)	Mg 1.0	Sand cast	T6	120	130	0.3	–	120	–	–	–	High performance
		Ni 1.0	Chill cast	T6	170	210	0.3	–	120	–	–	–	piston alloy
	(LM28)	Si 19.0	Chill cast	T5	170	190	0.5	–	120	–	–	–	
		Cu 1.5											
		Mg 1.0	Sand cast	T6	120	130	0.5	–	120	–	–	–	
		Ni 1.0	Chill cast	T6	170	200	0.5	–	120	–	–	–	
		Si 11.0	Chill cast	T5	–	220	1	–	105	–	–	–	Low expansion piston
		Cu 1.0											alloy
	(LM13)	Mg 1.0	Sand cast	T6	190	200	0.5	–	115	85*	–	–	
		Ni 1.0	Chill cast	T6	280	290	1	190	125	100*	1.4	–	

	Lo–Ex		Sand cast	T7	140	150	1	–	75	–	–	–	
			Chill cast	T7	200	210	1	–	75	–	–	–	
	(LM26)	Si 9.0 Cu 3.0 Mg 1.0 Ni 0.7	Chill cast	T5	180	230	1	–	105	–	1.4	–	Piston alloy
Al–Cu–Si–Mg–Fe–Ni	(3L52)	Cu 2.0 Si 1.5 Mg 1.0 Fe 1.0 Ni 1.25	Sand cast	T6	260	285	1	–	120	80	–	–	Aircraft engine castings for elevated temperature service
			Chill cast	T6	305	335	1	–	125	–	–	–	
Al–Cu–Si–Fe–Ni–Mg	(3L51)	Cu 1.5 Si 2.0 Fe 1.0 Ni 1.4 Mg 0.15	Sand cast	T5	135	170	2.5	–	70	–	–	–	Aircraft engine castings
			Chill cast	T5	150	210	3.5	–	75	–	–	–	

*Fatigue Limit for 50×10^6 cycles.
M = as manufactured.
H111 = annealed.
H2, H4, H5, H6 } intermediate tempers.
H8 = fully hard temper.

(1) Special temper for maximum stress corrosion resistance (US designation T73).
(2) Special heat treatment for combination of properties (US designation T736).
(3) Special heat treatment for combination of properties (US designation T61).
(4) Special heat treatment for combination of properties (US designation T7351).

Table 22.3 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*Time at temp. h*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong. % on 50 mm or* $5.65\sqrt{S_0}$
			Wrought Alloys					
Al (1095)	Al 99.95	Rolled rod	H111	24	–	–	55	61
				93	–	–	45	63
				203	–	–	25	80
				316	–	–	12	105
				427	–	–	5	131
(1200)	Al 99		H111	24	10 000	35	90	45
				100	10 000	35	75	45
				148	10 000	30	60	55
				203	10 000	25	40	65
				260	10 000	14	30	75
				316	10 000	11	17	80
				371	10 000	6	14	85
			H14	24	10 000	115	125	20
				100	10 000	105	110	20
				148	10 000	85	90	22
				203	10 000	50	65	25
				260	10 000	17	30	75
				316	10 000	11	17	80
				371	10 000	6	14	85
			H18	24	10 000	150	165	15
				100	10 000	125	150	15
				148	10 000	95	125	20
				203	10 000	30	40	65
				260	10 000	14	30	75
				316	10 000	11	17	80
				371	10 000	6	14	85
Al–Mn (3103)	Mn 1.25		H111	24	10 000	40	110	40
				100	10 000	37	90	43
				148	10 000	34	75	47
				203	10 000	30	60	60
				260	10 000	25	40	65
				316	10 000	17	30	70
				371	10 000	14	20	70
			H14	24	10 000	145	150	16
				100	10 000	130	145	16
				148	10 000	110	125	16
				203	10 000	60	95	20
				260	10 000	30	50	60
				316	10 000	17	30	70
				371	10 000	14	20	70
			H18	24	10 000	185	200	10
			H18	24	10 000	185	200	10
				148	10 000	110	155	11
				203	10 000	60	95	18
				260	10 000	30	50	60
				316	10 000	17	30	70
				371	10 000	14	20	70
Al–Mg (5050)	Mg 1.4		H111	24	10 000	55	145	–
				100	10 000	55	145	–
				148	10 000	55	130	–
				203	10 000	50	95	–
				260	10 000	40	60	–
				316	10 000	30	40	–
				371	10 000	20	30	–

Table 22.3 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES – *continued*

Material (specification)	*Nominal composition %*	*Condition*	*Temp. °C*	*Time at temp. h*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong. % on 50 mm or* $5.65\sqrt{S_0}$
			Wrought Alloys				
Al–Mg *(cont.)*		H14	24	10 000	165	195	–
			100	10 000	165	195	–
			148	10 000	150	165	–
			203	10 000	50	95	–
			260	10 000	40	60	–
			316	10 000	35	40	–
			371	10 000	20	30	–
		H18	24	10 000	200	220	–
			100	10 000	200	215	–
			148	10 000	175	180	–
			203	10 000	60	95	–
			260	10 000	40	60	–
			316	10 000	35	40	–
			371	10 000	20	30	–
Al–Mg–Cr (5052)	Mg 2.25 Cr 0.25	H111	24	10 000	90	195	30
			100	10 000	90	190	35
			148	10 000	90	165	50
			203	10 000	75	125	65
			260	10 000	50	80	80
			316	10 000	35	50	100
			371	10 000	20	35	130
		H14	24	10 000	215	260	14
			100	10 000	205	260	16
			148	10 000	185	215	25
			203	10 000	105	155	40
			260	10 000	50	80	80
			316	10 000	35	50	100
			317	10 000	20	35	130
		H18	24	10 000	255	290	8
			100	10 000	255	285	9
			148	10 000	200	235	20
			203	10 000	105	155	40
			260	10 000	50	80	80
			316	10 000	35	50	100
			371	10 000	20	35	130
(5154)	Mg 3.5 Cr 0.25	H111	24	10 000	125	240	25
			100	10 000	125	240	30
			148	10 000	125	195	40
			203	10 000	95	145	55
			260	10 000	60	110	70
			316	10 000	40	70	100
			371	10 000	30	40	130
		H14	24	10 000	225	290	12
			100	10 000	220	285	16
			148	10 000	195	235	25
			203	10 000	110	175	35
			260	10 000	60	110	70
			316	10 000	40	70	100
			371	10 000	30	40	130
		H18	24	10 000	270	330	8
			100	10 000	255	310	13
			148	10 000	220	270	20
			203	10 000	105	155	35
			260	10 000	60	110	70
			316	10 000	40	70	100
			371	10 000	30	40	130

continued overleaf

Table 22.3 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES – *continued*

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*Time at temp. h*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong. % on 50 mm or* $5.65\sqrt{S_0}$
			Wrought Alloys					
Al–Mg–Mn	Mg 5.0	As extruded	F	20	1000	145	300	25
(5056A)	Mn 0.3			50	1000	145	300	27
				100	1000	145	300	32
				150	1000	135	245	45
				200	1000	111	215	56
				250	1000	75	130	77
				300	1000	50	95	100
				350	1000	20	60	140
Al–Mg–Si	Mg 0.7		T6	24	10000	215	240	18
(6063)	Si 0.4			100	10000	195	215	15
				148	10000	135	145	20
				203	10000	45	60	40
				260	10000	25	30	75
				316	10000	17	20	80
				371	10000	14	17	105
(6082)	Mg 0.6		T6	24	10000	230	330	17
	Si 1.0			100	10000	270	290	19
	Cr 0.25			148	10000	175	185	22
				203	10000	65	80	40
				206	10000	35	45	50
				316	10000	30	35	50
				371	10000	25	30	50
(6061)	Mg 1.0		T6	24	10000	275	310	17
	Si 0.6			100	10000	260	290	18
	Cu 0.25			148	10000	213	235	20
	Cr 0.25			203	10000	105	130	28
				260	10000	35	50	60
				316	10000	17	30	85
				371	10000	14	20	95
Al–Cu–Mn	Cu 6	Forgings	T6	20	100	230	385	8
(2219)	Mn 0.25			100	100	–	365	–
				150	100	220	325	–
				200	100	185	280	–
				250	100	135	205	–
				300	100	110	145	–
				350	100	45	70	–
				400	100	20	30	–
Al–Cu–Pb–Bi	Cu 5.5		T4	24	10000	295	375	15
(2011)	Pb 0.5			100	10000	235	320	16
	Bi 0.5			148	10000	130	195	25
				203	10000	75	110	35
				260	10000	30	45	45
				316	10000	14	25	90
				371	10000	11	17	125
Al–Cu–Mg–Mn	Cu 4.0		T4	24	10000	275	430	22
(2017)	Mg 0.5			100	10000	255	385	18
	Mn 0.5			148	10000	205	274	16
				203	10000	115	150	28
				260	10000	65	80	45
				316	10000	35	45	95
				371	10000	25	30	100
(2024)	Cu 4.5		T4	24	10000	340	470	19
	Mg 1.5			100	10000	305	422	17
	Mn 0.6			148	10000	245	295	17
				203	10000	145	180	22
				260	10000	65	95	45
				316	10000	35	50	75
				371	10000	25	35	100

Table 22.3 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES – *continued*

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*Time at temp. h*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong. % on 50 mm or* $5.65\sqrt{S_0}$
				Wrought Alloys				
Al–Cu–Mg–Si–Mn (2014)	Cu 4.4 Mg 0.4 Si 0.8 Mn 0.8		T6	24	10 000	415	485	13
				100	10 000	385	455	14
				148	10 000	275	325	15
				203	10 000	80	125	35
				260	10 000	60	75	45
				316	10 000	35	45	64
				371	10 000	25	30	20
		Forgings	T6	20	100	415*	480	10
				100	100	410	465	–
				150	100	400	430	–
				200	100	260	295	–
				250	100	85	110	–
				300	100	45	70	–
				350	100	35	50	–
Al–Cu–Mg–Ni (2618)	Cu 2.2 Mg 1.5 Ni 1.2 Fe 1.0	Forgings	T6	20	100	325*	430	8
				150	100	340	440	–
				200	100	260	300	–
				250	100	170	210	–
				300	100	70	115	–
				350	100	30	50	–
				400	100	20	30	–
(2031)	Cu 2.2 Mg 1.5 Ni 1.2 Fe 1.0 Si 0.8	Forgings	T6	20	100	325*	430	13
				100	100	310	400	–
				200	100	255	310	–
				250	100	110	155	–
				300	100	45	75	–
				350	100	30	40	–
Al–Si–Cu–Mg–Ni (4032)	Si 12.2 Cu 0.9 Mg 1.1 Ni 0.9	Forgings	T6	24	10 000	320	380	9
				100	10 000	305	345	9
				148	10 000	225	255	9
				203	10 000	60	90	30
				260	10 000	35	55	50
				316	10 000	20	35	70
				371	10 000	14	25	90
Al–Zn–Mg–Cu (7075)	Zn 5.6 Cu 1.6 Mg 2.5 Cr 0.3		T6	24	10 000	505	570	11
				100	10 000	430	455	15
				148	10 000	145	175	30
				203	10 000	80	95	60
				260	10 000	60	75	65
				316	10 000	45	60	80
				371	10 000	30	45	65
				Cast alloys				
Al–Mg (LM 5)	Mg 5.0 Mn 0.5	Sand cast	F	20	1000	95	160	4
				100	1000	100	160	3
				200	1000	95	130	3
				300	1000	55	95	4
				400	1000	15	30	4
(LM 10)	Mg 10.0	Sand cast	T4	20	1000	180	340	16
				100	1000	205	350	10
				150	1000	154	270	0
				200	1000	105	185	42
				300	1000	40	90	85
				400	1000	11	45	100

continued overleaf

Table 22.3 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT ELEVATED TEMPERATURES – *continued*

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*Time at temp. h*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong. % on 50 mm or* $5.65\sqrt{S_0}$
				Cast Alloys				
Al–Si (LM 18)	Si 5.0	Pressure die cast	F	24	10000	110	205	9
				100	10000	110	175	9
				148	10000	103	135	10
				203	10000	80	110	17
				260	10000	40	55	23
(LM 6)	Si 12.0	Pressure die cast	F	24	10000	145	270	2
				100	10000	145	225	2(1/2)
				148	10000	125	185	3
				206	10000	105	150	7
				260	10000	40	75	13
Al–Si–Cu (LM 4)	Si 5.0 Cu 3.0 Mn 0.5	Sand cast	F	20	1000	95*	155	2
				100	1000	140	180	2
				200	1000	110	135	2
				300	1000	40	60	12
				400	1000	20	30	27
Al–Si–Mg (LM 25)	Si 5.0 Mg 0.5	Chill cast	T6	20	1000	270*	325	2
				100	1000	255	290	2
				200	1000	60	90	25
				300	1000	25	40	65
				400	1000	12	25	65
Al–Cu–Mg–Ni (4L 35)	Cu 4.0 Mg 1.5 Ni 2.0	Sand cast	T6	20	1000	200*	275	1/2
				100	1000	255	325	1/2
				200	1000	150	135	1/2
				300	1000	30	55	32
				400	1000	15	40	60
Al–Si–Ni–Cu–Mg (LM 13)	Si 12.0 Ni 2.5 Cu 1.0 Mg 1.0	Chill cast	T6	20	1000	275*	285	1/2
				100	1000	280	320	1/2
				200	1000	110	165	1/2
				300	1000	30	60	15
				400	1000	15	35	25
		Chill cast Special	T6	20	1000	200*	275	1
				100	1000	195	250	1
				200	1000	110	170	3
				300	1000	35	60	15
				400	1000	15	35	50

*0.1% Proof stress.

Table 22.4 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT LOW TEMPERATURES

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong.% on 50 mm or 50 mm*	*Reduction in area %*	*Fracture toughness* $MPa\,m^{1/2}$	*Reference*
Al (1200)	Al 99.0	Rolled and drawn rod	H111	24	34	90	42.5	76.4	–	
				−28	34	95	43.0	76.4	–	1
				−80	37	100	47.5	77.0	–	
				−196	43	170	56	74.4	–	
			H18	24	140	155	16	59.8	–	
				−28	144	155	152	59.4	–	1
				−80	147	165	18.0	65.3	–	
				−196	165	225	35.2	67.0	–	

Table 22.4 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT LOW TEMPERATURES – *continued*

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong.% on 50 mm or 50 mm*	*Reduction in area %*	*Fracture toughness MPa m$^{1/2}$*	*Reference*
Al–Mn (3103)	Mn 1.25	Rolled and drawn rod	H111	24	40	110	43.0	80.6	–	
				−28	40	115	44.0	80.6	–	1
				−80	50	130	45.0	79.9	–	
				−196	60	220	48.8	71.2	–	
		Rolled and drawn rod	H18	24	180	195	15.0	63.5	–	
				28	185	205	15.0	64.4	–	1
				−80	195	215	16.5	66.5	–	
				−196	220	290	32.0	62.3	–	
Al–Mg (5052)	Mg 2.5 Cr 0.25	Rolled and drawn rod	H111	24	97	199	33.2	72.0	–	
				−28	99	201	35.8	74.2	–	
				−80	97	210	40.8	76.4	–	
				−196	115	330	50.0	69.0		
			H18	24	235	275	16.6	59.1	–	
				−28	230	280	18.3	63.2	–	1
				−80	236	290	20.6	64.5	–	
				−196	275	400	30.9	57.4	–	
(5154)	Mg 3.5 Cr 0.25	Sheet	H111	26	115	240	28	66	–	
				−28	115	240	32	72	–	
				−80	115	250	35	73	–	
				−196	135	350	42	60	–	
			H18	26	275	330	9	–	–	
				−80	280	340	14	–	–	2
				−196	325	455	30	–	–	
				−253	370	645	35	–	–	
(5056A)	Mg 5.0 Mn 0.2	Plate	H111	20	130	290	30.5	32.0	–	
				−75	130	290	38.2	48.2	–	1
				−196	145	420	50.0	36.2	–	
Al–Mg–Si (6063)	Mg 0.7 Si 0.4	Extrusion	T4	26	90	175	32	78	–	
				−28	105	190	33	75	–	
				−80	115	200	36	75	–	
				−196	115	260	42	73	–	
		Extrusion	T6	26	215	240	16	36	–	
				−28	220	250	16	36	–	
				−80	225	260	17	38	–	
				−196	250	330	21	40	–	
Al–Mg–Si-Cr (6151)	Mg 0.7 Si 1.0 Cr 0.25	Forging	T6	24	300	320	15.2	38.8	–	
				−28	310	352	12.0	34.0	–	1
				−80	305	330	14.9	38.7	–	
				−196	330	385	18.3	34.7	–	
Al–Mg–Si–Cu–Cr (6061)	Mg 1.0 Si 0.6 Cu 0.25 Cr 0.25	Rolled and drawn rod	T6	24	270	315	21.8	56.4	–	
				−28	280	330	21.5	52.5	–	1
				−80	290	345	22.5	53.7	–	
				−196	315	425	26.5	46.5	–	
Al–Cu–Mg–Mn (2024)	Cu 4.5 Mg 1.5 Mn 0.6	Rolled and drawn rod	T4	24	300	480	23.3	31.8	–	
				−28	305	500	24.4	33.1	–	1
				−80	320	510	25.3	30.8	–	
				−196	400	615	26.7	26.3	–	
		Rolled and drawn rod	T8	24	400	500	14.5	25.8	–	
				−28	405	502	12.7	21.5	–	1
				−80	415	514	13.3	22.0	–	
				−196	460	605	14.0	19.7	–	

continued overleaf

Table 22.4 ALUMINIUM AND ALUMINIUM ALLOYS – MECHANICAL PROPERTIES AT LOW TEMPERATURES – *continued*

Material (specification)	*Nominal composition %*	*Condition*	*Temp. °C*	*0.2% Proof stress MPa*	*Tensile strength MPa*	*Elong.% on 50 mm or 50 mm*	*Reduction in area %*	*Fracture toughness MPa m$^{1/2}$*	*Reference*
Al–Cu–Si–Mg–Mn (2014)	Cu 4.5 Si 0.8 Mg 0.5 Mn 0.8	Rod T4	26	290	430	20	28	–	
			−28	290	440	22	28	–	
			−80	302	440	22	26	–	
			−196	380	545	20	20	–	
		Rod T6	26	415	485	13	31	–	
			−28	415	485	13	29	–	1
			−80	420	495	14	28	–	
			−196	470	565	14	26	–	
		Forging T6	26	410	465	12	24	–	
			−80	460	510	14	24	–	2
			−196	530	610	11	22	–	
			−253	590	715	7	22	–	
(2090)	Cu 2.7 Li 2.3 Zr 0.12	Plate (12.5 mm) T81	27	535	565	11	–	34	14
			−196	600	715	13.5	–	57	
			−269	615	820	17.5	–	72	
(2091)	Cu 2.1 Li 2.0 Mg 1.50 Zr 0.1	Plate (38 mm) T8	27	440	480	6	–	24	14
			−73	460	495	7	–	32	
			−196	495	565	10	–	32	
			−269	550	630	7	–	32	
Al–Zn–Mg–Cu (7075)	Zn 5.6 Mg 2.5 Cu 1.6	Rolled and drawn rod T6	24	485	560	15.0	29.1	–	
			−28	490	570	15.3	26.2	–	1
			−80	505	590	15.3	23.6	–	
			−196	570	670	16.0	20.1	–	

H111 = Annealed.
H18 = Fully hard temper.
T4 = Solution treated and naturally aged.
T6 = Solution treated and precipitation treated.

Table 22.5 ALUMINIUM ALOYS – CREEP DATA

Material (specification)	*Nominal composition %*	*Condition*	*Temp. °C*	*Stress MPa*	*Minimum creep rate % per 1000 h*	*Total extension % in 1000 h*	*Reference*
Al (1080)	99.8	Sheet H111	20	24.1	0.005	0.39	
			20	27.6	0.045	1.28	
			80	7.0	0.005	0.045	
			80	8.3	0.01	0.065	
			250	1.4	0.005	0.047	
			250	2.1	0.01	0.047	
			250	2.8	0.015	0.052	
			250	4.1	0.055	0.152	
Al–Mg (5052)	Mg	Sheet H111	80	45	0.005	0.085	
(LM 5)	Mg 5.6	Cast	100	110	0.055	0.33	3
			100	115	0.17	0.57	
			100	125	0.21	1.19	
			200	30	0.08	0.21	
			200	45	0.20	0.39	
			200	60	0.62	0.92	
			300	3.90	0.045	0.10	
			300	7.7	0.12	0.25	
			300	15	0.35	0.60	

Table 22.5 ALUMINIUM ALLOYS – CREEP DATA – *continued*

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*Stress MPa*	*Minimum creep rate % per 1000 h*	*Total extension % in 1000 h*	*Reference*
(LM 10)	Mg 10	Cast		100	40	0.013	0.126	3
				100	55	0.022	0.107	
				100	75	0.046	0.174	
				150	7.5	0.126	0.413	
				150	15	0.147	0.647	
				200	7.5	0.107	0.341	
				200	15	0.273	0.658	
Al–Cu	Cu 4	Cast		205	17	0.04	–	5
				205	34	0.09	–	
				205	51	0.14	–	
				205	70	0.69	–	
				315	8.90	0.13	–	
				315	13.1	0.29	–	
	Cu 10	Cast		205	34	0.01	–	5
				205	68	0.11	–	
				315	8.90	0.12	–	
				315	13.1	0.43	–	
				315	17	0.99	–	
Al–Si (LM 13)	Si 13 Ni 1.7 Mg 1.3	Sandcast (modified)		100	45	0.016	0.190	3
				100	60	0.06	0.675	
				200	15	0.016	0.096	
				200	23	0.054	0.179	
				200	30	0.14	0.432	
				300	3.8	0.013	0.026	
				300	7.7	0.047	0.098	
				300	15	0.223	0.428	
Al–Mn (3103)	Mn 1.25	Extruded rod		200	15	0.001	–	8
				200	31	0.022	–	
				200	34.8	0.040	–	
				200	38.6	0.060	–	
				200	42.5	0.13	–	
				200	46	0.15	–	
				200	54	0.73	–	
				300	7.5	0.007	–	
				300	15	0.39	–	
Al–Cu–Si (2025)	Cu 4 Si 0.8	Extruded	T4	150	90	0.03	0.340	3
				150	125	0.045	0.395	
				150	155	0.325	0.722	
				200	30	0.035	0.107	
				200	45	0.1	0.204	
				200	60	0.040	0.700	
				250	15	0.02	0.156	
				250	23	0.07	0.176	
				250	30	2.36	–	
Al–Cu–Mg–Mn (2024)	Cu 4.5 Mg 1.5 Mn 0.6	Clad sheet	T4	35	415	10.0	–	4
				100	344	1.0	–	
				100	385	10.0	–	
				150	276	1.0	–	
				150	327	10.0	–	
				190	140	1.0	–	
				190	200	10.0	–	

continued overleaf

Table 22.5 (*continued*)

Material (specification)	*Nominal composition %*	*Condition*		*Temp. °C*	*Stress MPa*	*Minimum creep rate % per 1000 h*	*Total extension % in 1000 h*	Reference
Al–Cu–Mg–Mn (2024) (*contd*)	Cu 4.5 Mg 1.5 Mn 0.6	Clad sheet	T6	35	424	1.0	–	4
				35	430	10.0	–	
				100	347	1.0	–	
				100	363	10.0	–	
				150	242	1.0	–	
				150	289	10.0	–	
				190	117	1.0	–	
				190	193	10.0	–	
Al–Cu–Mg–Ni (2218)	Cu 4 Mg 1.5 Ni 2.2	Forged	T4	100	193	0.01	0.394	3
				100	232	0.02	0.440	
				100	270	0.04	0.835	
				200	77	0.028	0.173	
				200	108	0.16	0.345	
				300	7	0.037	0.078	
				300	15	0.5	0.640	
				400	1.5	0.05	0.110	
		Cast	T4	200	77	0.01	0.153	3
				200	116	0.08	0.287	
				300	7	0.018	0.072	
				300	15	0.08	0.151	
				400	1.50	0.06	0.132	
Al–Cu–Mg–Zn (7075)	Zn 5.6 Cu 1.6 Mg 2.5	Clad sheet	T6	35	430	0.1	–	4
				35	480	1.0	–	
				35	495	10.0	–	
				100	295	0.1	–	
				100	355	1.0	–	
				100	370	10.0	–	
				150	70	0.1	–	
				150	170	1.0	–	
				150	245	10.0	–	
				190	45	0.1	–	
				190	75	1.0	–	
				190	125	10.0	–	
Al–Mg–Si–Mn (6351)	Mg 0.7 Si 1.0 Mn 0.6	Extruded rod		100	193	0.007	–	8
				100	201	0.010	–	
				100	232	0.11	–	
				100	255	1.6	–	
				150	93	0.0087	–	
				150	108	0.023	–	
				150	154	0.22	–	
				200	31	0.011	–	
				200	46	0.040	–	
				200	62	0.13	–	
				200	77	0.28	–	

H111 = Annealed.
T4 = Solution treated and naturally aged, will respond to precipitation treatment.
T6 = Solution treated and artificially aged.

Table 22.6 ALUMINIUM ALOYS – FATIGUE STRENGTH AT VARIOUS TEMPERATURES

Material (specification)	*Nominal composition %*	*Condition*	*Temp. °C*	*Endurance (unnotched) MPa*	*MHz*	*Remarks*	*Reference*
Al–Mg (5056)	Mg 5.0	Extruded	−65	184	20	Rotating beam	
			−35	164			
			+20	133			

Table 22.6 (*continued*)

Material (specification)	*Nominal composition %*	*Condition*	*Temp. °C*	*Endurance (unnotched) MPa*	MHz	*Remarks*	*Reference*
	Mg 7.0	Extruded rod	−65	182	20	Rotating beam	
			−35	178			
			+20	173			
(LM 10)	Mg 10.0	Sand cast (oil quenched)	20	93	30	Rotating beam	9
			150	77			
			200	40			
Al–Si (LM 6)	Si 12.0	Sand cast (modified)	20	51	50	Rotating beam, 24 h at temp.	6
			100	43			
			200	35			
			300	25			
Al–Cu (2219)	Cu 6.0	Forged T6	20	117	120	Reverse bending stresses	9
			150	65			
			200	62			
			250	46			
			300	39			
			350	23			
Al–Si–Cu (LM 22)	Si 4.6 Cu 2.8	Sand cast	20	62	50	Rotating beam	6
			100	54			
			200	60			
			300	42			
Al–Cu–Si–Mn (2014)	Cu 4.5 Si 0.8 Mn 0.8	Forgings T6	148	65	100	Rotating beam	
			203	45			
			260	25			
Al–Cu–Mn–Mg (2014)	Cu 4.0 Mn 0.5 Mg 0.5	Extruded rod T4	25	103	500	Rotating beam, 100 days at temp.	7
			148	93			
			203	65			
			260	31			
Al–Cu–Mg–Si–Mn (2014)	Cu 4.4 Mg 0.7 Si 0.8 Mn 0.8	Forgings T4	20	119	120	Reversed bending	9
			150	90			
			200	62			
			250	54			
			300	39			
		Forgings T6	20	130	120	Reversed bending	9
			150	79			
			200	57			
			250	39			
			300	39			
Al–Cu–Mg–Ni (2218)	Cu 4.0 Mg 1.5 Ni 2.0	Forged	20	117	500	Rotating beam after prolonged heating	
			148	103	100		
			203	65	100		
			260	45	100		
		Chill cast T6	20	100	50	Rotating beam, 24 h at temp.	6
			100	105			
			200	108			
			300	80			
Al–Ni–Cu	Ni 2.5 Cu 2.2	Forged T6	20	113	120	Reversed bending	9
			150	82			
			200	70			
			250	59			
			300	39			
			350	39			

continued overleaf

Table 22.6 (*continued*)

Material (specification)	*Nominal composition %*	*Condition*	*Temp. °C*	*Endurance (unnotched) MPa*	*MHz*	*Remarks*	*Reference*
Al–Si–Cu–Mg–Ni (LM 13)	Si 12.0 Cu 1.0 Mg 1.0	Chill cast (Lo-Ex)	20 100 200 300	97 107 97 54	50	Rotating beam, 24 h at temp.	6
Al–Zn–Mg–Cu (7075)	Zn 5.6 Mg 2.5 Cu 1.6 Cr 0.2	Plate T6	24 149 204 260	151 83 59 48	500	Reversed bending	–

T4 = Solution treated and naturally aged, will respond to precipitation treatment.
T6 = Solution treated and artificially aged.

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FURTHER INFORMATION

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2. *Metals Handbook*, Vol. 2, 10th Edition, ASM International, 1990.

22.2 Mechanical properties of copper and copper alloys

22.2.1 Standard specifications

United Kingdom – British Standards – BS designation

BS 1400	Copper alloy ingots and copper and copper alloy castings
2870	Rolled copper and copper alloys, sheet, strip and coil
2871	Copper and copper alloys – tubes
2872	Copper and copper alloys – forgoing stock and forgings
2873	Copper and copper alloys – wire
2874	Copper and copper alloys – rods and sections
2875	Copper and copper alloys – plate

International Standards Organization – ISO designation

ISO/R1190-1	1971 Copper and copper alloys. Parts 1 and 2

ISO 426/I	1973 Wrought copper-zinc alloys. Part 1
ISO 426/II	1973 Wrought copper-zinc alloys Part 2
ISO 427	1973 Wrought copper-tin alloys
ISO 428	1973 Wrought copper-aluminium alloys
ISO 429	1973 Wrought copper-nickel alloys
ISO 430	1973 Wrought copper-nickel-zinc alloys
ISO 431	1972 Electrolytic tough pitch copper
ISO R197	1961 Classification of coppers
ISO R1187	1971 Special wrought copper alloys
ISO R1190-1	1971 Copper and copper alloys. Parts 1 and 2

22.2.2 CEN standards

The international Standards Organization (ISO) in Technical Report TR7003 published an International Numbering System for Metals. This has led to the European CEN standards numbering xsystem. CEN/TC 132 agreed to use C as the first letter to denote copper and copper alloys. The second letter indicates the material state: W for wrought material; B for ingots; C for castings; and M for master alloys. There follows three numbers that uniquely identify the material. The sixth position is a letter that defines the material group. These for copper alloys are as follows: A and B for copper; C for miscellaneous copper alloys (max 5% alloying elements); E and F for miscellaneous copper alloys (over 5% alloying elements); G for copper-aluminium alloys; H for copper-nickel alloys; J for copper-nickel-zinc alloys; K for copper-tin alloys; L and M for copper-zinc binary alloys; N and P for copper-zinc-lead alloys; R for copper-zinc alloys complex; and A–S for copper materials not standardized by CEN/TC 133 with letters as appropriate to the material group.

Typical examples are as follows:

Material	*ISO Symbols*	*CEN Numbers*
Coppers	Cu-ETP	CW004A
	Cu-OF	CW008A
Wrought Brasses	CuZn37	CW508L
	CuZn39Pb3	CW614N
	CuZn20AlAs	CW702R
	CuZn40Mn1pb1AlFeSn	CW721R
Other wrought alloys	CuNi2Si	CW111C
	CuAl10Fe1	CW305G
	CuNi30Mn1Fe	CW354H
Cast alloys	CuZn33Pb2-GB	CB750S
	CuZn33Pb2-GS	CC750S
	CuSn12-GB	CB483K
	CuSn12-GS	CC483K
Master Alloys	CuAl50(A)-M	CM344G
	CuCr10-M	CM204E
	CuS20-M	CM220E

Temper designations are also given by CEN TC133. For copper and copper alloys letters are used for mandatory properties as follows: A – elongation, B – spring bending limit, G – grain size, H – hardness (Brinell for castings, Vickers for wrought products), M – as manufactured, R – tensile strength, Y – 0.2% proof stress.

For further reference to the CEN system for Copper, contact the Copper Development Association or their CD ROM *Megabytes on Copper*.

As the CEN standard has not yet been adopted in the UK, the ISO designation has been used in Column 1 of Table 22.7 and the current BS specification numbers have been used in Column 2 of Table 22.7 and in Table 22.8.

Table 22.7 COPPER AND COPPER ALLOYS—TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

Condition of material is expressed in accordance with BS Nomenclature, viz:

- O — Material in the annealed condition
- ¼H, ½H, H, EH — The various harder tempers produced by cold rolling. For certain of the materials in this schedule, these tempers may be produced by partial annealing
- SH, ESH — Spring hard tempers produced by cold rolling of thinner material
- M — Material in the 'as manufactured' condition. In this schedule confined to hot rolled or extruded material
- W — Material which has been solution heat treated and will respond effectively to precipitation treatment
- W(¼H), W(½H), W(H) — Material which has been solution heat treated and subsequently cold worked to various harder tempers
- WP — Material which has been solution heat treated and precipitation treated
- W(¼H)P, W(½H)P, W(H)P — Material which has been solution heat treated, cold worked and then precipitation treated

British Standards gives strengths in $N\,mm^{-2}$ – numerically equal to MPa. $1\,N\,mm^{-2} \equiv 1$ MPa.

Material and composition	*British Standard specification number*	*Condition*	*Limit of proportionality* MPa	*0.2% Proof stress* MPa	UTS MPa	*Elongation on 5d or 50 mm* %	*Shear strength* MPa	*Brinell hardness* kg mm^{-2}	*Vickers hardness* (10 kgf)	*Modulus of elasticity* GPa
Oxygen-free Cu 99.95% + high conductivity Cu 99.99% + copper	BS 2870 C 103	Strip—O	15	48	216	48	162	42	51	117
	BS 3839 C 110	Strip—½H	198	176	263	32	170	82	90	
		Strip—H	154	265	314	16	185	96	106	
Tough pitch copper $O_2 = 0.03\%$	BS 2870 C 101	Strip—O	31	54	224	56	162	49	53	
		Strip—½H	116	176	263	29	170	74	88	
		Strip—H	154	270	314	13	185	87	107	
										117
	BS 2873 and BS 2874 C 101	Wire and Rod—O	—	—	232	45	—	—	—	
		H (Over 5 mm dia.)	—	—	370	—	—	—	—	
		H (Under 5 mm dia.)	—	—	448	—	—	—	—	

Phosphorus-deoxidized non-arsenical copper P 0.04	BS 2875 BS 2871 Pt. 1 C 106	Plate M	31	54	239	58	162	54	58	117
		Tube—½H	—	170	263	30	—	82	90	
Deoxidized arsenical copper P 0.03% As 0.35%	BS 2875 C 107	Plate—M	31	54	239	56	162	50	54	117
Silver-bearing copper Ag 0.05%	BS 2870 C 101 (+ silver)	Strip—O	31	54	224	56	162	55	59	117
		Strip—½H	—	180	286	25	178	75	80	
		Strip—H	—	263	316	10	185	90	100	
Tellurium copper	BS 2874 C 109	Rod—O	—	54	232	40	140	49	53	117
Te 0.5%		Rod—½H	—	232	278	15	185	80	85	
Chromium copper Cr 0.6%	BS 2874 CC 102	Rod—W	28	54	232	60	150	58	65	—
		Rod—WP	247	324	448	25	280	124	142	
		Rod—W(H)	309	479	541	14	—	140	160	
Beryllium copper Be 1.85 Co 0.25	BS 2870 CB 101	Strip—W	—	224	479	47	—	100	110	159
		Strip—WP	—	1 066	1 205	7	540	350	360	
		Strip—W(H)	—	1 205	1 313	2	—	363	380	
Be 0.5 Co 2.5	—C 112	Strip—W	—	178	324	27	220	67	75	159
		Strip—WP	—	618	757	11	360	205	210	
		Strip—WH	—	772	810	8	370	215	220	
Cadmium copper Cd 0.8	BS 2873 C 108	Wire—H	—	600	649	—	350	—	—	124
Sulphur copper	BS 2874 C 111	Rod—O	—	54	216	40	140	50	55	117
S 0.35		Rod—½H	—	231	263	12	185	80	85	
Cap copper Cu 95 Zn 5		Strip—O	39	92	263	45	192	65	70	124
		Strip—½H	124	223	308	30	216	85	89	
		Strip—H	162	315	386	8	232	105	110	
Gilding metals Cu Zn 10	BS 2870 CZ 101	Strip—O	39	100	262	60	216	65	70	124
		Strip—½H	124	247	317	24	224	85	90	
		Strip—H	173	324	386	8	247	100	110	

Table 22.7 COPPER AND COPPER ALLOYS—TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE—*continued*

Material and composition	*British Standard specification number*	*Condition*	*Limit of proportionality* MPa	*0.2% Proof stress* MPa	UTS MPa	*Elongation on 5d or 50 mm* %	*Shear strength* MPa	*Brinell hardness* kg mm^{-2}	*Vickers hardness* (10 kgf)	*Modulus of elasticity* GPa
Cu Zn 15	BS 2870 CZ 102	Strip—O	39	108	293	60	224	65	70	121
		Strip—½H	142	254	340	28	239	85	90	
		Strip—H	193	370	440	12	285	125	130	
Cu Zn 20	BS 2870 CZ 103	Strip—O	46	108	317	64	230	65	70	119
		Strip—½H	170	285	378	30	247	100	105	
		Strip—H	216	402	479	16	285	130	140	
Brasses Cu Zn 30	BS 2870 CZ 106	Strip—O	46	115	324	67	230	65	70	115
		Strip—½H	154	270	378	40	247	107	115	
		Strip—H	208	386	463	20	254	132	143	
Cu Zn 33	BS 2870 CZ 107	Strip—O	54	115	331	60	247	65	70	112
		Strip—½H	154	278	388	35	263	110	117	
		Strip—H	208	432	510	12	293	140	150	
Cu Zn 37	BS 2870 CZ 108	Strip—O	70	131	331	55	278	65	70	108
		Strip—½H	170	285	402	28	293	110	117	
		Strip—H	210	402	494	10	309	136	145	
Cu Zn 40	BS 2874 CZ 123	Rod—½H	—	309	424	20	300	120	125	102
	BS 2875 CZ 123	Plate—M	62	130	371	40	278	85	90	
Aluminium brass Cu Zn 22 Al 2	BS 2871 CZ 110	Tube—O	—	139	378	55	269	75	80	110
	BS 2875 CZ 110	Plate—M	—	154	393	50	285	95	100	
Naval brass Cu Zn 36 Sn 1	BS 2874 CZ 112	Rod—M	93	170	408	35	316	100	105	103
		Plate—M	77	124	386	40	285	90	95	
Free cutting brass Cu Zn 39 Pb 3	BS 2874 CZ 121	Rod—M	—	201	417	25	309	105	110	96
Hot stamping brass Cu Zn 40 Pb 2	BS 2874 CZ 122	Rod—M	—	224	402	30	316	95	100	96

High tensile brass Cu Zn 39 Fe Mn	BS 2874 CZ 115	Rod—M	93	210	440	30	309	95	150	103
High tensile brass Cu Zn 39 Al Fe Mn	BS 2874 CZ 114	Rod—M	139	290	520	30	340	—	160	103
Nickel silvers Cu Ni 10 Zu 27	BS 2879 NS 103	Strip—O	62	100	340	65	280	66	69	121
		Strip—½H	170	332	432	28	290	121	158	
		Strip—H	270	510	564	11	320	155	177	
Cu Ni 12 Zn 24	BS 2870 NS 104	Strip—O	62	108	340	60	290	65	68	124
		Strip—H	309	587	695	4	400	210	220	
Cu Ni 15 Zn 21	BS 2870 NS 105	Strip—O	77	124	355	55	290	70	74	121
		Strip—H	340	618	695	4	400	210	220	
Cu Ni 18 Zn 20	BS 2870 NS 106	Strip—O	70	124	386	52	300	77	81	121
		Strip—½H	91	386	486	21	390	138	155	
		Strip—H	123	525	610	7	430	166	168	
Cu Ni 25 Zn 18	BS 2870 NS 109	Strip—O	77	124	386	50	—	75	80	121
		Strip—H	309	618	695	4	—	201	210	
Phosphor bronzes Cu Sn 3 P	BS 2870 PB 101	Strip—O	54	124	324	50	247	70	74	121
		Strip—½H	300	386	510	12	340	160	170	
		Strip—H	402	579	656	2	378	195	205	
Cu Sn 5 P	BS 2870 PB 102	Strip—O	54	130	347	55	254	71	75	122
		Strip—½H	362	440	541	14	347	165	175	
		Strip—H	479	618	710	2	386	205	215	
Cu Sn 7 P	BS 2870 PB 103	Strip—O	77	139	356	60	260	80	84	117
		Strip—½H	371	494	593	12	371	175	185	
		Strip—H	494	687	741	5	424	210	220	
Cu Sn 8 P	—	Wire—O	—	—	424	65	309	—	—	111
		Wire—H	—	—	927	—	440	—	—	
Copper-nickel Cu Ni 5 Fe	BS 2871 CN 101	Tube—O	—	116	316	35	240	65	70	132
		Plate—M	—	93	278	40	201	60	65	

Table 22.7 COPPER AND COPPER ALLOYS—TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE —*continued*

Material and composition	*British Standard specification number*	*Condition*	*Limit of proportionality* MPa	*0.2% Proof stress* MPa	UTS MPa	*Elongation on 5d or 50 mm* %	*Shear strength* MPa	*Brinell hardness* kg mm^{-2}	*Vickers hardness* (10 kgf)	*Modulus of elasticity* GPa
Cu Ni 10 Fe Mn	BS 2871 CN 102	Tube—O	—	139	331	38	247	70	74	135
		Plate M	..	108	324	40	240	65	70	
Cu Ni 30 Fe Mn	BS 2871 CN 107	Tube—O	—	170	417	42	309	90	95	152
		Plate—M	—	161	355	38	278	90	95	
Silicon bronze	BS 2870 CS 101	Plate—M	—	—	410	55	—	—	—	103
Cu 96 Si 3 Mn 1		Rod—O	—	77	362	60	293	—	—	
Aluminium bronzes Cu Al 5	BS 2870 CA 101	Plate—M	—	147	378	50	286	85	90	126
Cu Al 8 Fe 3	BS 2875 CA 105	Plate—M	—	170	417	45	316	90	95	123
		Rod—½H	—	479	602	12	378	160	170	
Cu Al 10 Ni 5 Fe 4	BS 2874 CA 104	Rod—H	—	417	757	18	571	200	210	131
Sn 7 P 0.1	BS 2870 PB 103	Strip—O	77	139	356	60	260	80	84	117
		Strip—½H	371	494	593	12	371	175	185	
		Strip—H	494	687	741	5	424	210	220	
Sn 8 P 0.5	—	Wire— O	—	—	424	65	309	—	—	111
		Wire—H	—	—	927	—	440	—	—	
Copper-nickels	BS 2871 CN 101	Tube—O	-	116	316	35	240	65	70	132
Ni 5.5 Fe 1.2 Mn 0.5		Plate—M	—	93	278	40	201	60	65	
Ni 10.5 Fe 1.0 Mn 0.75	Bs 2871 CN 102	Tube—O	—	139	331	38	247	70	74	135
		Plate—M	—	108	324	40	240	65	70	

Ni 31.0 Fe 1.0 Mn 1.0	BS 2871 CN 107	Tube—O	—	170	417	42	309	90	95	152
		Plate M	—	161	355	38	278	90	95	
Silicon bronze	BS 2870 CS 101	Plate M	—	—	410	55	—	—	—	103
Cu 96 Si 3 Mn 1		Rod—O	—	77	362	60	293	—	—	
Aluminium bronzes Cu 95 Al 5	BS 2870 CA 101	Plate—M		147	378	50	286	85	90	126
Cu 92 Al 8	—	Plate—M	—	170	417	45	316	90	95	123
		Rod—½H	—	479	602	12	378	160	170	
Cu 85.5 Al 9.5 Fe 3.0 Mn 1.0 Ni 1.0	BS 2874 CA 103	Rod—H	—	417	757	18	571	200	210	131

Table 22.8 CAST COPPER—TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE
(Properties vary, dependent on composition, section size and foundry practice)

BS 1400 *designation*	*Material*	*Composition* %	*Condition*	0.2% *Proof stress* N mm^{-2}	*UTS* N mm^{-2}	*Elongation on* 50 mm %	*Brinell hardness*
SCB1	Brass for sand castings	Cu 64 Zn 34 Pb 2	Sand cast	77	232	25	45–60
LG2	Leaded gunmetal	Cu 85 Pb 5 Sn 5 Zn 5	Sand cast Continuous cast	108 124	216 254	15 20	65–75 75–95
HTB1	High tensile brasses	Cu 56 Al 1.5 Fe 1.5 Mn 1.5 Zn 39.5	Sand cast Centrifugal cast	201 224	494 587	20 22	100–150 100–150
HTB3		Cu 56 Al 5 Fe 2.5 Mn 2.5 Zn 34	Sand cast Centrifugal cast	386 403	710 757	12 15	150–230 150–230
G1	Gunmetal	Cu 88 Sn 10 Zn 2	Sand cast *Continuous cast	139 147	286 317	18 15	50–70 70–90
LB2	Leaded bronze	Cu 80 Sn 10 Pb 10	Sand cast *Continuous cast	108 170	247 293	18 20	65–85 80–90
PB1	Phosphor bronze	Cu 90 Sn 10	Sand cast *Centrifugal cast	139 185	293 370	15 16	70–100 100–150
AB1	Aluminium bronzes	Cu 87 Al 10 Fe 3	Sand cast *Centrifugal cast	201 216	541 571	25 28	90–140 120–160
AB2		Cu 80 Al 10 Fe 5 Ni 5	Sand cast *Centrifugal cast	263 293	649 695	15 15	140–180 140–180
AB3	Aluminium silicon bronze	Cu 95.5 Al 6 Si 2	Sand cast	180	460	20	90–140

* Properties of continuously cast and centrifugally cast materials are generally similar.

Table 22.9 COPPER AND COPPER ALLOYS—TYPICAL TENSILE PROPERTIES AT ELEVATED TEMPERATURES
Limit of proportionality or proof stress is reported under a code, viz:

LP = Limit of proportionality
0.1 = 0.1% offset proof stress
0.2 = 0.2% offset proof stress
0.5 = 0.5% offset proof stress

Material	*Composition* %	*Condition (see Table 22.7)*	*Temperature* °C	*Limit of proportionality or proof stress* MPa	*Code (see above)*	*UTS* MPa	*Elongation on 50 mm* %	*Remarks*	*Reference*
Oxygen-free high conductivity copper	Cu 99.99+	Sheet—O	24	78	0.2	212	56.3	Average grain size 0.045 mm	2
			100	77	0.2	190	55.4		
			204	70	0.2	159	56.9		
Tough-pitch copper	O_2 0.03	Sheet—O	24	68	0.5	214	57.8	Average grain size 0.043 mm	2
			100	68	0.5	187	57.4		
			204	67	0.5	157	56.9		
Phosphorus-deoxidized non-arsenical copper	P = 0.04	Sheet—Q	24	65	0.5	210	53.4	Average grain size 0.044 mm	2
			100	66	0.5	183	52.5		
			204	57	0.5	161	52.1		
Deoxidized arsenical copper	As 0.35 P 0.03	Plate—M	20	93	0.1	219	57	Hot rolled plate	2
			121	93	0.1	204	57		
			204	83	0.1	184	52		
Silver-bearing copper	Ag 0.05	Sheet—O	20	48	0.1	227	53	Average grain size 0.03 mm	2
			300	45	0.1	162	45		
			500	32	0.1	107	42		
Tellurium copper	Te 0.5	Rod—H	27	350	0.2	361	12.8		2
			260	265	0.2	266	4.7		
Chromium copper	Cr—0.6	Rod—O	20	—	—	259	35	Strain rate 0.1 in min^{-1}	4
			350	—	—	204	44		
			550	—	—	148	10		
		Rod—WP	20	—	—	374	21	Strain rate 0.1 in min^{-1}	4
			350	—	—	298	10		
			550	—	—	210	3		
Gilding metals Cu Zn 10	Cu 90 Zn 10	Rod—O	25	—	—	253	56	—	2
			375	—	—	137	9	—	
			635	—	—	59	17	—	
			875	—	—	19	16	—	
Cu Zn 15	Cu 85 Zn 15	Plate—O	20	79	0.1	297	50	—	2
			121	79	0.1	259	45	—	
			232	74	0,1	238	36	—	
Cu Zn 20	Cu 80 Zn 20	Rod—H	23	—	—	557	13	Cold worked 30%	2
			400	—	—	143	7		
			850	—	—	10	30		
Brasses Cu Zn 30	Cu 70 Zn 30	Strip—O	20	99	0.1	332	64	Grain size 0.03 mm	2
			200	93	0.1	293	54		
			300	88	0.1	238	32		
Cu Zn 37	Cu 63 Zn 37	Strip—O	20	125	0.1	347	60	Grain size 0.035 mm	2
			200	120	0.1	317	54		
			300	111	0.1	267	39		
Cu Zn 40	Cu 60 Zn 40	Plate—O	20	96	0.2	332	62	—	2
			121	96	0.2	312	62		
			204	105	0.2	297	62		

Table 22.9 COPPER AND COPPER ALLOYS—TYPICAL TENSILE PROPERTIES AT ELEVATED TEMPERATURES *—continued*

Material	*Composition* %	*Condition (see Table 22.7)*	*Temperature* °C	*Limit of proportionality or proof stress* MPa	*Code (see above)*	*UTS* MPa	*Elongation on* 50 mm %	*Remarks*	*Reference*
Aluminium brass	Cu 76 Al 2 Zn 22	Tube—O	20 200 400	165 134 108	0.2 0.2 0.2	397 317 232	53.8 38.5 13.3	Elongation measured on $11.3\sqrt{\text{area}}$	2
Naval brass	Cu 62 Sn 1 Zn 37	Plate—O	21 121 204	141 133 134	0.1 0.1 0.1	360 246 326	47 46 38	— —	2
Free cutting brass	Cu 58 Zn 39 Pb 3	Rod—M	21 482	266 —	LP —	477 76	33.5	—	2
Forging brass	Cu 59 Zn 39 Pb 2	Rod—O	20 200 400 610	— — — —	— — — —	364 319 163 34	50.2 42.2 25.4 22.5		2
High tensile brass	Cu 59.32 Zn 35.95 Fe 2.07 Al 1.21 Pb 0.71 Sn 0.67	Rod—O	27 232 427	207 193 —	0.5 0.5 —	479 314 208	13 28 47	Extruded and annealed 816°C for 20 min	5
Nickel silver 20% Ni	Cu 75 Ni 20 Zn 5	Rod—O	30 316 399	76 86 —	LP LP —	347 310 272	51.0 28.5 37.0	—	—
Phosphor bronze	Sn 5 P 0.1	Rod—O	17 260 500	— 100 65	— 0.2 0.2	337 278 141	84 34 6	—	2
	Sn 8 P 0.05	Tube—H	20 200 400	441 451 304	0.2 0.2 0.2	559 539 345	47 37 6	Temper hard and stress relieved	2
Silicon bronze	Si 3 Mn 1	Strip—O	20 200 300	104 94 92	0.1 0.1 0.1	371 309 276	66 54 52	Strain rate 2 in min^{-1}	—
Copper-nickels	Ni 5.5 Fe 1.2 Mn 0.5	Plate—O	20 177 316	158 134 133	0.1 0.1 0.1	301 255 230	40 38 34	—	2
	Ni 10.5 Fe 1.0 Mn 0.75	Tube—O	20 204 400	159 147 139	0.1 0.1 0.1	371 329 287	35 28 18	—	2
	Ni 31.0 Fe 1.0 Mn 1.0	Plate—M	20 232 371	114 96 86	0.1 0.1 0.1	369 304 283	50 46 63	Hot rolled	2
Aluminium bronze	Cu 89 Al 8 Fe 3	Rod—M	20 300 500	294 69 10	0.2 0.2 0.2	490 441 147	51 31 58	Extruded rod elongation measured on $11.3\sqrt{\text{area}}$	
Cu Al 10 Fe 5 Ni 5	Cu 79.9 Al 10.0 Ni 4.8 Fe 4.8 Mn 0.4	Rod—M	20 200 400	556 510 263	0.2 0.2 0.2	848 817 310	17 18 35	Extruded rod elongation measured on $4.5\sqrt{\text{area}}$	

Table 22.10 COPPER AND COPPER ALLOYS—TYPICAL TENSILE AND IMPACT PROPERTIES AT LOW TEMPERATURES

Limit of proportionality or proof stress is reported under a code, viz:

LP = Limit of proportionality
0.1 = 0.1% offset proof stress
0.2 = 0.2% offset proof stress
0.5 = 0.5% offset proof stress

Impact values are reported either as C = Charpy, V notch test or I = Izod test

				Proof stress			*Elongation*	*Impact value*		
Material	*Composition* %	*Condition*	*Temperature* °C	MPa	*Code (see above)*	*UTS* MPa	*on* 50 mm %	Joules	*Code (see above)*	*Reference*
Oxygen-free high conductivity copper	Cu 99.99+	Rod—O	Room	75	0.2	222	86.2	71.1	C	2
			−78	80	0.2	270	84.5	77.1	C	
			−253	90	0.2	418	83.0	85.8	C	
Tough pitch copper	O_2 0.03	Rod—O	+20	59	0.1	216	48.0	58.3	I	2
			−80	69	0.1	266	47.0	59.6	I	
			−180	79	0.1	351	57.6	67.7	I	
Beryllium copper	Cu 97.44 Be 2.56	Rod—W	+20	171	0.1	525	36	55.5	I	
			−80	201	0.1	598	38	54.2	I	
			−180	344	0.1	769	41	54.2	I	
		Rod—WP	+20	865	0.1	1287	2.6	2.7	I	6
			−80	1016	0.1	1388	0.4	4.1	I	
			−180	1069	0.1	1480	3.0	4.1	I	
Gilding metals	Cu 90 Zn 10	Rod—O	+22	66	0.2	265	56 Measured	151.8	C	2
			−197	91	0.2	381	86 on 4.52	151.8	C	
			−269	147	0.2	470	91 $\sqrt{}$area	—		
Brasses	Cu 70 Zn 30	Rod—O	+20	194	0.1	352	49.4	88.8	I	2
			−80	188	0.1	394	59.5	93.5	I	
			−180	204	0.1	507	74.6	106.4	I	
	Cu 60 Zn 40	Rod—O	+20	—	—	397	51.3	41.8	C	
			−78	—	—	421	53.0	42.0	C	2
			−183	—	—	523	55.3	40.7	C	
		Rod—H (Cold worked 25% reduction)	+20	—	—	549	19.8	—	—	
			−78	—	—	571	21.0	—	—	
			−183	—	—	669	24.4	—	—	
Free cutting brass	Cu 58 Zn 39 Pb 3	Rod—H	+20	—	—	559	27	—	—	
			−80	—	—	598	27	—	—	2
			−195	—	—	735	26	—	—	

Table 22.10 COPPER AND COPPER ALLOYS—TYPICAL TENSILE AND IMPACT PROPERTIES AT LOW TEMPERATURES—*continued*

Limit of proportionality or proof stress is reported under a code, viz:

LP = Limit of proportionality
0.1 = 0.1% offset proof stress
0.2 = 0.2% offset proof stress
0.5 = 0.5% offset proof stress

Impact values are reported either as C = Charpy, V notch test or I = Izod test

Material	*Composition* %	*Condition*	*Temperature* °C	*Proof stress* MPa	*Code* (*see above*)	*UTS* MPa	*Elongation* on 50 mm %	*Impact value* Joules	*Code* (*see above*)	*Reference*
Forging brass	**Cu 58**	**Rod—O**	**+ 20**	—	—	**364**	**50.2**	**21.5**	C	
	Zn 40		− 78	—	—	377	49.8	24.1	C	2
	Pb 2		−183	—	—	475	50.6	22.6	C	
Phosphor bronzes	Cu 95	Sheet—O	+ 27	155	0.2	358	61	—	—	
	Sn 9		− 40	173	0.2	393	73	—	—	2
			− 73	180	0.2	427	76	—	—	
		Sheet—EH	+ 27	621	0.2	677	7	—	—	
			− 40	648	0.2	703	9.5	—		
			− 73	677	0.2	738	11	—		
	Cu 92	Rod—H	+ 24	772	0.2	807	20 (On 1 in	—	—	
	Sn 8		−196	964	0.2	986	30 gauge	—	—	2
			−253	1059	0.2	1158	25 length)	—	—	
Silicon bronze	Cu 96	Rod—H	+ 25	—	—	511	39.8	—	—	
	Si 3	(Cold worked	− 80	—	—	571	31.7	—	—	6
	Mn 1	42% reduction)	−190	—	—	692	36.2	—	—	
Nickel silver	Cu 55.15	Sheet—O	+ 20	193	0.1	519	33	108.5	I	
	Ni 30.5		−120	199	0.1	619	38	108.5	I	6
	Zn 14.3		−190	196	0.1	718	41	118.0	I	
Copper-nickels	Ni 10.5	Rod—O	+ 22	147	0.5	342	37 On	154.6	C	
	Fe 1.0		−197	208	0.5	569	50 $4.52\sqrt{\text{area}}$	155.9	C	2
	Mn 0.5		−269	172	0.5	556	53	—	—	
	Ni 31.0	Rod—O	+ 22	129	0.5	398	47 On	155.9	C	
	Fe 1.0		−197	218	0.5	619	52 $4.52\sqrt{\text{area}}$	154.6	C	2
	Mn 1.0		−253	263	0.5	715	51	154.6	C	
Aluminium bronzes	Cu 92	Rod—O	+ 25	110	0.2	414	107 Gauge length	—	—	2
	Al 8		−196	134	0.2	558	77 not quoted	—		
	Cu 79	Plate—M	+ 20	415	0.2	745	12 On	19.3	C	2
	Al 10		−196	588	0.2	892	4 $5.65\sqrt{\text{area}}$	8.3	C	
	Fe 5									
	Mn 1									
	Ni 5									

Table 22.11 COPPER AND COPPER ALLOYS—FATIGUE PROPERTIES AT ROOM TEMPERATURE
Note: Where the number of cycles is not given the value represents endurance limit.

Material	*Composition* %	*Form and condition*	*Fatigue strength* MPa	*Number of cycles* 10^6	*Reference*
Oxygen-free high conductivity copper	Cu 99.9+	Rod—cold worked 29.2%	117	300	2
Tough pitch copper	O_2—0.03	Rod—annealed Grain size—0.040 mm	62	300	2
		Wire—cold worked 37%	107	100	
Deoxidized non-arsenical copper	P—0.04	Tube—annealed Grain size 0.050 mm	76	20	2
		Strip—cold rolled 60% reduction	128	100	
Silver-bearing copper	Ag—0.03	Strip-cold rolled 50% reduction	103	—	7
Chromium copper	Cr = 0.88 Si —0.09 Fe —0.07	Rod—cold drawn 90% reduction	178	300	7
		Rod—cold drawn 90% reduction—heat treated 3 h 400°C	193	300	
Beryllium coppers	Be = 1.85 Co = 0.25	Strip—solution heat treated	224	100	3
		Strip—rolled 'hard'after solution heat treatment	239	100	
		Strip—rolled 'hard' after solution heat treatment and then precipitation hardened	284	100	
	Be —0.6 Co = 2.5	Strip—rolled '½ hard' after solution treatment	241	100	
Gilding metal	Cu = 90 Zn = 10	Strip—annealed Grain size 0.030 mm	69	100	2
		Strip—cold worked 21% reduction	110	100	
		Strip—cold worked 37% reduction	114	100	
		Strip—cold worked 60% reduction	124	100	
		Strip—cold worked 68% reduction	138	100	
	Cu = 80 Zn = 20	Strip—annealed Grain size 0.035 mm	97	100	2
		Strip—cold worked 60% reduction	152	100	
Brasses	Cu = 70 Zn —30	Strip—annealed Grain size 0.025 mm	107	100	2
		Strip—cold rolled 21% reduction	124	100	
		Strip—cold rolled 60% reduction	152	100	
	Cu —65 Zn —35	Strip—annealed	104	100	2
		Strip—cold rolled 37.1% reduction	135	100	
		Strip—cold rolled 60.5% reduction	138	100	

Table 22.11 COPPER AND COPPER ALLOYS—FATIGUE PROPERTIES AT ROOM TEMPERATURE—*continued*

Material	*Composition* %	*Form and condition*	*Fatigue strength* MPa	*Number of cycles* 10^6	*Reference*
Brass (cont.)	Cu = 60 Zn = 40	Rod—annealed Rod—cold worked 25% and stress relieved at 275°C	148 210	100 100	2
Aluminium brass	Cu = 76 Zn = 22 Al = 2	Rod—cold worked 20–25% and stress relieved	97	20	2
Naval brass	Cu = 62 Zn = 38 Sn = 1	Rod—hot rolled Rod—cold worked 27% reduction	128 183	100 100	2
Phosphor bronze	Sn = 5 P = 0.1	Strip—annealed Grain size 0.035 mm Strip—cold rolled 69% reduction	172 221	100 100	2
	Sn = 8 P = 0.1	Rod—annealed Grain size 0.020 mm Rod—cold worked 30.1% reduction	221 234	1 000 1 000	2
	Sn = 10 P = 0.1	Rod—annealed Grain size—0.065/070 mm Rod—cold worked 30.1% reduction	172 159	1 000 1 000	2
Silicon bronze	Cu = 96 Si = 3 Mn = 1	Rod—annealed Rod—hard	130 232	300 300	7
Copper-nickels	Ni = 5.5 Fe = 1.0 Mn = 0.5	Rod—annealed Rod—cold worked 25% reduction	131 173	100 100	2
	Ni = 10.5 Fe = 1.5 Mn = 0.75	Strip—cold rolled Hard temper	145	100	2
	Ni = 31.0 Fe = 1.0 Mn = 1.0	Tube—annealed Tube—cold worked and stress relieved	147 177	100 100	2
Aluminium bronze	Cu = 92 Al = 8	Rod—lightly worked	203	100	2
	Cu = Rem. Al = 9.7 Fe = 5.1 Ni = 5.3	Rolled rod	323	100	2
Nickel silver	Cu = 55 Ni = 18 Zn = 27	Strip—annealed Strip—cold rolled 70% reduction	114 173	100 100	—

Table 22.12 COPPER AND COPPER ALLOYS, IMPACT PROPERTIES

Material	*Composition* %	*Form and condition*	*Temperature* °C	*Impact value* *Izid* Joules	*Charpy* Joules	*Reference*
Oxygen-free high conductivity copper	Cu 99.99 +	Plate—hot rolled	0	—	62.4	1
			204	—	50.2	
			316	—	56.9	
			538	—	44.7	
			650	—	35.3	
Tough pitch copper	O_2 0.08	Plate—annealed	20	47.5	—	8
			200	37.9	—	
			300	35.3	—	
			500	31.2	—	
			600	28.5	—	
Phosphorus-deoxidized non-arsenical copper	P 0.06	Plate—annealed	20	61.0	—	8
			200	56.9	—	
			300	55.6	—	
			500	42.0	—	
			600	31.2	—	
Deoxidized arsenical copper	As 0.36 P 0.07	Plate—annealed	20	62.4	—	8
			200	56.9	—	
			400	55.6	—	
			500	43.4	—	
			600	31.2	—	
Naval brass (American type)	Cu 60.25 Sn 0.75 Zn Bal.	Annealed	20	—	82.4	6
			−50	—	79.9	
			−80	—	84.7	
			−115	—	80.6	
Phosphor bronze	Sn 4 P 0.4	Rod—hard drawn	20	62.4	—	9
			−41	59.7	—	
Silicon bronze	Cu 96 Si 3 Mn 1	Rod—annealed	20	—	90.0	6
			−50	—	99.1	
			−80	—	93.8	
			−115	—	87.4	
Aluminium bronzes	Cu 89.6 Al 7.8 Fe 2.6	Rod—extruded annealed and roller straightened	24	—	98.9	
			−29	—	105.7	
			−59	—	103.0	
			−182	—	94.9	
	Cu 81.2 Al 10.1 Ni 4.75 Mn 0.8	Rod—extruded annealed and roller straightened	24	—	20.3	
			−29	—	19.0	
			−59	—	17.6	
			−182	—	12.2	
Copper-nickels	Cu 80 Ni 20	Annealed	20	104.4	—	6
			−80	107.1	—	
			−120	113.9	—	
			−180	115.2	—	
	Cu 70 Ni 30	Annealed	20	—	89.9	6
			−30	—	80.5	
			−50	—	80.5	
			−80	—	79.6	
			−115	—	81.3	
Nickel silvers	Cu 74.28 Ni 19.49 Zn 5.43 Mn 0.80	Annealed	20	—	91.5	6
			−30	—	76.5	
			−50			
			−80	—	75.7	
			−115	—	71.3	
	Cu 55.15 Ni 30.50 Zn 14.3	Annealed	20	—	108.4	—
			−40	—	118.0	
			−120	—	108.5	
			−180	—	118.0	

Table 22.13 WROUGHT COPPER AND COPPER ALLOYS. CREEP PROPERTIES

Notes: (1) All values relate to rod or wire products unless specified.
(2) Total extension = Initial extension + total creep.
= Initial extension + intercept + (minimum creep rate × duration)

Materials and composition %	*Condition*	*Test temperature* °C	*Applied stress* MPa	*Duration* 1 000 h	*Total extension* %	*Intercept* %	*Minimum creep rate in* % *per* 1 000 h	*Remarks*
Oxygen-free copper Cu 99.99 +	Annealed grain size 0.025 mm	149	14.5	6.4	0.053	0.024	0.001 7	Reference 2
			21.0	6.5	0.128	0.049	0.007 5	
			31.4	6.0	0.510	0.290	0.023	
			54.8	5.1	2.490	1.560	0.083	
		204	14.2	6.5	0.213	0.054	0.021	
			21.3	6.0	0.580	0.256	0.049	
			28.0	6.5	1.295	0.727	0.078	
			51.0	5.0	4.580	2.670	0.215	
	Hard drawn 84% reduction	149	54.6	6.0	0.102	0.002	0.008 2	
		204	14.5	3.2	0.157	0.090	0.014	
			28.0	6.0	0.422	0.185	0.0345	
			48.3	6.5	3.80	2.50	0.19	
HC copper $O_2 = 0.04$		149	14.2	6.4	0.088	0.048	0.003 2	Reference 2
			20.7	6.5	0.257	0.133	0.013	
			41.4	6.5	1.875	1.120	0.057 5	
			55.9	6.5	3.475	1.795	0.088	
	Annealed grain size 0.025 mm	260	2.5	6.0	0.084	0.016	0.011	
			7.3	6.5	0.640	0.113	0.079 5	
			13.7	6.5	2.877	0.869	0.306	
	Drawn 84% reduction	149	52.0	6.4	0.118	0.041	0.004 9	
			68.9	6.5	0.167	0.042	0.010	
		204	7.3	6.5	0.064	0.045	0.001 1	
			28.0	6.5	1.080	0.409	0.097	
			49.0	6.5	5.418	2.47	0.44	
Deoxidized non-arsenical copper P = 0.008	Annealed grain size 0.032 mm	204	14.2	6.0	0.078	0.037	0.003 9	Reference 2
			21.0	7.08	0.355	0.164	0.018 5	
			35.1	7.08	1.378	0.660	0.051	
			55.4	6.0	3.334	1.120	0.120	
	Cold worked 84% reduction	204	24.4	7.7	0.126	−0.015 1	0.0152	Reference 2
			34.7	7.08	0.119	−0.085	0.038	Accelerating creep rate
			62.4	7.08	0.534	−1.110	0.224	Accelerating creep rate
			103.5	0.58	0.169	0.034	0.055	
			103.5	4.2	2.813	−8.630	2.70	Accelerating creep rate
Deoxidized arsenical copper As = 0.35 P = 0.03	Annealed grain size 0.045 mm	149	20.7	6.5	0.055	0.013	< 0.000 1	
			35.8	6.4	0.580	0.085	0.002 35	
			54.8	6.5	1.560	0.185	0.008 5	
			70.6	6.4	2.537	0.275	0.019	
		204	21.0	6.0	0.119	0.040	0.002 3	
			38.6	6.0	1.055	0.295	0.014	Reference 2
			49.0	6.0	1.648	0.365	0.022	
		260	14.2	6.86	0.107	0.049	0.005 5	
			24.4	6.86	0.678	0.335	0.024	
			43.1	6.0	2.584	0.700	0.152	
	Cold worked 84% reduction	149	85.6	6.4	0.089	0.017	0.000 24	
			138.8	6.5	0.153	0.033	0.000 5	
			207.6	6.5	0.282	0.089	0.001 6	
			275.8	9.45	0.452	0.118	0.007 8	
			325.4	0.5	0.750	0.160	0.42	
			325.4	0.75	0.910	—	—	
		260	10.7	6.0	0.029	0.001 5	0.001 45	
			14.2	6.0	0.075	−0.012	0.012	Accelerating creep rate
			24.4	7.3	0.605	−0.187	0.105	Accelerating creep rate
			34.4	6.5	0.933	−0.672	0.24	Accelerating creep rate

Table 22.13 WROUGHT COPPER AND COPPER ALLOYS, CREEP PROPERTIES—*continued*

Materials and composition %	*Condition*	*Test temperature* °C	*Applied stress* MPa	*Duration* 1 000 h	*Total extension* %	*Intercept* %	*Minimum creep rate in* % *per* 1 000 h	*Remarks*
Silver-bearing copper Ag–0.086 O_2–0.02	Annealed strip grain size 0.030 mm	130	137.9	2.4	15.8	14.7	1.05	Reference 2
			96.5	2.6	7.0	6.7	0.35	
		175	137.9	2.4	27.4	23.2	1.85	
		225	41.2	3.0	0.9	0.6	0.02	
			96.5	2.5	10.6	8.0	1.1	
	Cold worked strip 25% reduction	130	55.1	4.75	0.08	0.075	0.002	Reference 2
			96.5	10.2	0.18	0.16	0.004	
			137.9	7.2	0.26	0.24	0.005	
		225	55.1	8.9	0.21	0.14	0.006 4	
			96.5	11.5	0.56	0.38	0.017	
	Cold worked strip 50% reduction	130	55.1	4.55	0.09	0.08	0.001 5	
			96.5	11.4	0.20	0.185	0.001 5	
			137.9	7.25	0.29	0.265	0.004	
		225	55.1	8.9	0.26	0.15	0.011	
			96.5	12.9	0.795	0.335	0.029	
			137.9	3.0	0.825	0.525	0.10	
Tellurium copper Te–0.5	Annealed grain size 0.025 mm	149	21.0	6.0	0.134 4	0.077	0.001 4	Reference 2
			35.8	6.0	0.251 5	0.121	0.007 8	
			59.0	6.0	1.553	0.737	0.022 3	
	Cold drawn 37%	149	47.6	6.0	0.089 5	0.034 4	0.000 85	
			68.9	6.0	0.149 4	0.068 1	0.001 9	
			103.5	6.0	0.223 4	0.088	0.005 2	
			137.5	6.0	0.390 5 5	0.155 5	0.011 5	
			201.3	6.0	1.133	0.479	0.080	
Cadmium copper Cd = 1.03	Cold worked 20% reduction	103	137.9	—	—	—	0.007	Reference 5
		205	55.1	—	—	—	0.011	
			137.9	—	—	—	0.075	
Chromium copper Cr = 0.73	Fully heat treated and drawn	343	68.9	—	—	—	0.008 9	Reference 5
			110.3	—	—	—	0.014	
			137.9	—	—	—	0.038	
Cap copper Cu 95 Zn 5	Cold drawn 51% reduction	200	98.1	3.305	0.123	—	—	Reference 2
			117.7	1.995	0.21	—	—	
			137.3	1.999	0.38	—	—	
			140.2	2.011	0.51	—	—	
Gilding metal Cu 85 Zn 15	Annealed grain size 0.060 mm	149	31.0	4.5	0.031	0.006	0.000 7	Reference 2
			48.0	5.1	0.087	0.024	0.002 9	
			67.6	4.5	1.07	0.44	0.026	
		260	13.9	5.0	0.091	0.026	0.008	
			24.2	5.3	0.241	0.037	0.030	
			34.3	5.0	0.507	0.083	0.073	
			41.3	5.14	0.958	0.180	0.138	
			47.9	1.6	1.100	0.510	0.32	
	Cold worked 84% reduction	149	66.9	4.4	0.096	0.029	0.000 7	
			136.5	5.1	0.197	0.054	0.000 2 6	
			273.7	4.5	0.445	0.108	0.011	
			371.0	5.1	0.860	0.250	0.033	
		260	4.2	5.54	0.096	0.038	0.010	
			6.6	5.3	0.270	0.080	0.034	
			13.4	2.95	0.678	0.104	0.19	
			20.5	3.65	2.715	−0.045	0.76	Accelerating creep rate
Brass Cu 70 Zn 30	Annealed grain size 0.022 mm	204	19.3	3.3	0.052	0.016	0.008 1	Reference 2
			39.2	1.6	0.104	0.025	0.036	
			59.2	3.3	0.430	0.035	0.11	
		260	7.7	4.8	0.115	0.014	0.021	
			13.3	3.72	0.357	0.061	0.074	
			18.8	4.08	0.908	0.090	0.195	
			25.3	3.72	1.557	0.147	0.37	

Table 22.13 WROUGHT COPPER AND COPPER ALLOYS, CREEP PROPERTIES—*continued*

Materials and composition %	*Condition*	*Test temperature* °C	*Applied stress* MPa	*Duration* 1 000 h	*Total extension* %	*Intercept* %	*Minimum creep rate in* % *per* 1 000 h	*Remarks*
Brass	Cold worked	149	68.9	5.2	0.156	0.058	0.002 5	Reference 2
Cu 70	84% reduction		135.8	5.23	0.326	0.129	0.005 4	
zU 30	(fine grained)		275.4	6.85	0.780	0.260	0.026	
(contd)			348.8	4.75	1.430	0.540	0.10	
		204	6.9	5.1	0.128	0.084	0.006 7	
			21.2	5.06	0.530	0.180	0.063 6	
			34.7	4.7	1.494	0.213	0.265	
		260	3.4	5.0	0.311	0.121	0.037	
			5.6	5.0	0.970	0.175	0.159	
			10.2	2.62	3.015	0.212	1.07	
Brass	Annealed	149	34.4	6.43	0.053 5	0.009 5	0.001 1	Reference 2
Cu 60			51.3	6.43	0.099	0.029	0.002 3	
Zn 40			68.9	6.43	0.158	0.039	0.006	
			103.4	6.43	0.313	0.084	0.011 5	
			137.1	6.43	3.580	1.265	0.20	
		204	7.3	7.7	0.048	0.013 2	0.002 9	
			14.2	7.7	0.090	0.025	0.005 8	
			28.0	2.28	0.18	0.010	0.022	
			42.0	7.68	1.975	0.053	0.246	
Forging brass	Extruded and	149	68.9	—	—	—	0.052	Reference 5
Cu 59.32	annealed	177	68.9	—	—	—	0.18	
Zn 35.95	816°C for	204	68.9	—	—	—	0.92	
Pb 2.07	20 mm	260	68.9	—	—	—	89.0	
		177	20.7	—	—	—	0.030	
		232	20.7	—	—	—	0.075	
		260	20.7	—	—	—	0.134	
		288	20.7	—	—	—	1.14	
Admiralty	Annealed grain	149	31.4	4.5	0.029	0.013	<0.001	Reference 2
brass	size 0.055 min		82.3	3.38	0.090	0.023	0.001 4	
Cu 70			104.4	4.4	0.134	0.042	0.002 8	
Zn 29		260	6.6	4.98	0.026	0.003	0.003 7	
Sn 1			13.6	4.3	0.072	0.031	0.008	
			20.7	4.98	0.149	0.034	0.021	
			31.0	4.3	0.306	0.019	0.062	Accelerating creep rate
			42.5	6.3	1.528	−0.35	0.295	Accelerating creep rate
	Cold worked	149	86.5	5.2	0.164	0.066	0.001 6	Reference 2
	60% reduction		103.5	6.5	0.203	0.078	0.002 7	
			138.5	5.4	0.287	0.116	0.005 2	
			208.8	6.5	0.451	0.179	0.008 8	
			280.7	5.2	0.685	0.307	0.018	
			361.5	5.2	1.053	0.385	0.060	
		260	2.0	5.75	0.088	0.052	0.005 5	
			6.8	2.95	0.425	0.090	0.11	
			13.7	5.3	2.481	0.160	0.435	
			20.4	2.6	2.601	0.340	0.86	
Aluminium	Annealed	149	40.6	5.5	0.037 5	0.002	0.001 0	Reference 2
brass	grain size		68.3	6.5	0.099	0.024	0.003 8	
Cu 76	0.030 mm		137.1	6.5	0.450	0.146	0.029	
Zn 22			151.7	9.45	0.979	0.367	0.051	
Al 2		260	3.8	6.86	0.097	0.043	0.007 1	
			7.3	6.86	0.298	0.082	0.030	
			10.7	6.5	0.524	0.128	0.059	
	Cold worked	149	132.0	6.4	0.208	0.074	0.002 8	
	37% reduction		207.6	6.5	0.349	0.128	0.006 3	
			275.1	11.1	0.590	0.233	0.010	
			344.7	6.5	1.169	0.498	0.054	
		260	7.3	6.0	0.159	0.081	0.012	
			14.4	6.0	0.577	0.197	0.061	
			21.0	6.0	1.243	0.117	0.184	
			34.7	3.48	2.322	−0.181	0.71	

Table 22.13 WROUGHT COPPER AND COPPER ALLOYS. CREEP PROPERTIES—*continued*

Materials and composition %	*Condition*	*Test temperature* °C	*Applied stress* MPa	*Duration* 1 000 h	*Total extension* %	*Intercept* %	*Minimum creep rate in* % *per* 1 000 h	*Remarks*
Phosphor bronze Cu 95 Sn 5 P 0.2	Annealed grain size 0.050 mm	149	31.0	5.62	0.028	0.003	0.000 3	
			68.9	5.62	0.072	0.009	0.000 8	
			104.1	5.62	0.142	0.016	0.001 9	
			117.5	4.75	0.978	0.008	0.009 4	
		260	10.7	5.1	0.039	0.017	0.001 6	
			17.0	5.0	0.066	0.020	0.005	
			34.3	5.8	0.216	0.065	0.018	
			72.7	5.64	1.191	−0.100	0.213	Accelerating creep rate
	Cold worked 84% reduction	149	31.5	5.62	0.045	0.009	0.000 9	Reference 2
			103.0	5.62	0.170	0.050	0.002 6	
			136.5	5.65	0.235	0.075	0.003 7	
			205.4	5.62	0.367	0.112	0.008	
			344.4	4.75	0.726	0.250	0.027	
		260	2.2	5.1	0.113	0.025	0.016 4	
			3.7	5.64	0.285	0.090	0.033 6	
			6.80	8.15	0.797	0.269	0.063 4	
			20.8	5.75	2.511	−0.243	0.47	Accelerating creep rate
Silicon bronze Cu 96 Si 3 Mn 1	Annealed 450°C	204	86.5	—	—	—	0.065	Reference 11
			103.5	—	—	—	0.084	
		288	34.6	—	—	—	0.035	
			41.4	—	—	—	0.080	
			51.9	—	—	—	0.19	
			69.0	—	—	—	0.65	
Aluminium bronze Cu 95 Al 5	Annealed plate	200	107.8	3.0	0.2	—	0.000 07	
		300	33.4	2.0	0.2	—	0.000 1	
	Cold drawn (rod)	550	17.3	5.8	7.5	0.035	640	Rupture test results
	Rockwell 92B		34.4	0.52	5.7	0.62	8 340	Reference 2
		600	6.8	85.3	23.5	0.090	79	
			17.3	2.9	8.5	0.316	1 250	
			34.4	0.14	8.0	0.0	23 500	
Aluminium bronze Cu 79 Al 10 Fe 5 Mn 1 Ni 5	Extruded	250	61.8	1.17	0.068	—	< 0.004 2	Reference 2
			92.7	1.44	0.123	—	0.008 3	
			139.0	1.44	0.236	—	0.0317	
			216.2	1.27	0.622	—	0.258 3	
			308.9	1.128	3.67	—	—	
		400	46.3	0.72	0.43	—	0.237 5	
			61.8	0.72	0.76	—	0.5417	
			77.2	0.72	1.93	—	1.375	
Copper-nickel Ni 10.5 Fe 1.0 Mn 0.5	Annealed grain size 0.025 mm	149	103.5	6.0	0.870 5 5	0.1	< 0.000 1	Reference 2
			137.9	6.0	2.131	0.242	0.000 16	
			172.4	6.0	4.705	0.1637	0.000 22	
		260	63.5	6.0	1.090	0.143 6	0.000 61	
			90.7	6.0	0.516	0.253 8	0.001 7	
			126.6	6.0	1.803	0.175 6	0.003 8	
	Cold worked 21% reduction	149	138.2	6.0	0.139 1	0.018 8	< 0.000 1	
			206.8	6.0	0.199	0.0148	0.000 2	
			276.1	6.0	0.277	0.027 6	0.001 4	
			310.3	6.0	0.410	0.061	0.002 4	
			343.2	6.0	0.635	0.164	0.003 5	
		260	139.9	6.0	0.198 8	0.057 6	0.002 2	
			207.9	6.0	0.442 5	0.169	0.0136	
			244.8	4.32	0.607	0.189	0.044	
			244.8	6.0	0.700	0.102	0.061 7	

Table 22.13 WROUGHT COPPER AND COPPER ALLOYS, CREEP PROPERTIES—*continued*

Materials and composition %	*Condition*	*Test temperature* °C	*Applied stress* MPa	*Duration* 1 000 h	*Total extension* %	*Intercept* %	*Minimum creep rate in* % *per* 1 000 h	*Remarks*
Copper-nickel	Cold worked	399	124.2	2.5	0.219	—	0.015	Reference 2
Ni 31	and stress		172.4	2.5	0.319	—	0.032	
Fe 1	relieved		206.8	1.5	0.359	—	0.055	
Mn 1			241.4	1.0	0.490	—	0.17	
			275.8	1.0	0.818	—	0.40	
			310.3	1.0	3.25	—	1.0	
		454	48.3	2.5	0.142	—	0.019	
			96.5	1.5	0.339	—	0.072	
			172.4	1.0	0.993	—	0.61	
			206.8	1.5	9.80	—	2.2	
		510	13.7	1.5	0.096	—	0.032	
			41.4	1.0	0.292	—	0.18	
			124.2	1.5	11.2	—	3.4	
		566	10.3	0.5	0.185	—	0.3	
			68.9	0.5	7.20	—	7	
Nickel silver	Annealed 650	316	34.4	—	0	—	—	Reference 11
Cu 74.23			86.5	—	0.006	—	—	
Ni 20.08			103.5	—	0.013	—	—	
Zn 5.08			137.5	—	0.034	—	—	
Mn 0.69			173.0	—	0.072	—	—	
		399	34.4	—	0	—	—	
			61.8	—	0.015	—	–	
			86.5	—	0.065	—	–	
			103.5	—	0.365	—	—	

Table 22.14 CAST COPPER ALLOYS—CREEP PROPERTIES

Material and composition %	*Test temperature* °C	*Applied stress* MPa	*Minimum creep rate in* % per 1 000 h	*Reference*
High tensile brass	149	69	0.118	
Cu 57.14				
Al 0.44	177	69	0.69	
Sn 0.10				11
Pb 0.49	288	21	1.81	
Fe 1.72				
Zn 40.11				
Silicon brass	260	69	0.075	
Cu 81.6				
Zn 13.95	316	21	0.236	
Si 4.40				
Fe 0.05	371	21	0.73	5
		69	35	
Aluminium bronze—sand cast	250	77	<0.146	
Cu 90		131	<0.153	
Al 10		185	<1.44	10
		309	400	
Aluminium bronze—sand cast	250	77	<0.037 5	
Cu 80		131	<0.121	10
Al 10		185	<0.321	
Fe 5		309	<1.85	
Ni 5				

Table 22.14 CAST COPPER ALLOYS—CREEP PROPERTIES —*continued*

Material and composition %	*Test temperature* °C	*Applied stress* MPa	*Minimum creep rate in* % per 1 000 h	*Reference*
Leaded gun metal	232	55	0.007	
Cu 84.8		76	0.032	5
Pb 4.8		97	0.140	
Sn 5.1	260	41	0.007	
Zn 4.8		45	0.013	
		55	0.040	
Tin bronze	260	103	1.44	
Cu 90		55	0.042	
Sn 19				5
	316	69	2.0	
		55	0.89	
		28	0.225	
		7	0.030	
Admiralty gun metal	204	93	0.039	
Cu 88		120	0.75	
Sn 10				
Zn 2	260	42	0.0195	
		62	0.023 5	12
		76	0.06	
	316	21	0.011	
		28	0.013	
		35	0.138	

Table 22.15 TENSILE AND CREEP PROPERTIES OF TOUGH PITCH COPPER-SILVER ALLOYS[13]

Silver %	*Cold work* %	*Test temp.* °C	0.2% *Proof stress* MPa	*UTS* MPa	*Elong. on* 50 mm %	*Stress for* 1% *strain in* 10^5 *hours* MPa	*Stress for rupture in* 10^5 *hours* MPa
0.002	0	RT	64	220	49	—	—
	0	100	63	193	50	42	107
	0	150	63	176	50	39	59
	30	RT	287	307	18	—	—
	30	100	262	270	10	—	120
	30	150	244	253	14	—	67
0.034	0	RT	73	225	53	—	—
	0	100	73	197	52	—	142
	0	150	62	182	52	—	112
	10	RT	199	241	35	—	—
	10	100	189	209	34	159	167
	10	150	178	192	36	134	137
	20	RT	291	297	13	—	—
	20	100	260	266	8	—	—
	20	150	244	248	7	—	—
	30	RT	296	303	11	—	—
	30	100	267	277	8	182	189
	30	150	253	260	8	139	147
0.065	0	RT	83	225	50	—	—
	0	100	81	199	52	70	151
	0	150	75	185	50	63	119
	10	RT	212	245	34	—	—
	10	100	204	215	30	168	179
	10	150	190	201	28	142	148
	20	RT	293	296	12	—	—
	20	100	275	278	7	—	—
	20	150	259	261	7	—	—
	30	RT	299	304	10	—	—
	30	100	277	282	7	203	215
	30	150	263	268	7	142	166

Table 22.15 TENSILE AND CREEP PROPERTIES OF TOUGH PITCH COPPER-SILVER ALLOYS[13]—*continued*

Silver %	*Cold work* %	*Test temp.* °C	0.2% *Proof stress* MPa	*UTS* MPa	*Elong. on* 50 mm %	*Stress for* 1% *strain in* 10^5 *hours* MPa	*Stress for rupture in* 10^5 *hours* MPa
0.14	0	RT	67	230	51	—	—
	0	100	66	203	51	74	—
	0	150	69	189	53	65	144
	10	RT	205	249	36	—	—
	10	100	198	219	32	176	192
	10	150	189	203	30	153	166
	20	RT	288	296	12	—	—
	20	100	272	276	8	230	238
	20	150	261	263	7	200	204
	30	RT	328	337	7	—	—
	30	100	308	314	6	253	265
	30	150	290	306	5	198	217
0.32	0	RT	82	232	52	—	—
	0	100	74	206	52	83	—
	0	150	82	194	51	66	—
	10	RT	194	249	41	—	—
	10	100	184	221	36	—	—
	10	150	186	211	35	—	—
	20	RT	278	289	18	—	—
	20	100	267	272	10	—	—
	20	150	255	261	9	—	—
	30	RT	330	336	11	—	—
	30	100	314	317	7	282	280
	30	150	299	308	6	241	249

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22.3 Mechanical properties of lead and lead alloys

The mechanical properties of lead and its alloys, particularly the more dilute alloys, are extremely sensitive to variations in composition, grain size, metallurgical history and temperature and rate of testing. They are therefore rarely reproducible with any degree of accuracy, except on the same sample under identical test conditions and, even then, a delay of a few hours between tests may affect the results obtained.

The figures quoted in the following tables should therefore be considered only as *typical* and should not be used where accuracy is necessary. For these same reasons, the materials quoted in the tables are grouped according to their principal uses and the typical values quoted for various properties are merely intended as an indication of their suitability for those uses.

Lead alloys are also dealt with under 'Solders', Chapter 34.

Table 22.16 LEAD AND LEAD ALLOYS—TYPICAL MECHANICAL PROPERTIES

Common name	*Nominal composition* %	*Specification*[1] (BS)	*Hardness DPN*	*Tensile strength*[2] MPa	*Fatigue*[3] *strength* MPa
A. Lead and lead alloys for chemical applications					
Type A lead	Pb > 99.99	334 Type A	4	16.8 (20 °C) 12.1 (60 °C)	±3.17 (20°C) ±2.24 (60 °C)
Copper lead	Cu 0.05–0.07	334 Type B1	4.5	17.6 (20 °C) 15.2 (60 °C)	±4.96 (20°C) ±4.69 (60°C)
Tellurium copper lead	Te 0.02–0.05 Cu 0.05–0.07	334 Type B2	6	21.1 (20 °C) 18.7 (60 °C)	±7.24 (20°C) ±6.55 (60°C)
Silver copper lead	Ag 0.003–0.005 Cu 0.003–0.005	334 Type B3	5	16.4 (20°C) 13.4 (60°C)	±4.48 (20°C) ±3.45 (60°C)
Antimonial lead	Sb 2.5–11.0	334 Type C			
	Sb 4.0		8–12	30.0 (20°C) 25.2 (60°C)	±10.62 (20°C) ±10.04 (60°C)
	Sb 8.0		9–16	37.7 (20°C) 35.9 (60°C)	±14.82 (20°C) ±12.06 (60°C)
Dispersion strengthened lead[4]	PbO 1.5 dispersed phase	—	14	29.4	±13.4
	PbO 4.0 dispersed phase	—	—	35.5	±13.7
B. Lead and lead alloys for building applications					
Milled (rolled) lead sheet[8]	Pb > 99.9	1178[5]	4	15–18[6]	±2.9[7]
Lead pipes (not chemical)	Pb > 99.8	602[5] Comp. I	4	17[6]	±2.9[7]
	Pb 99.25–99.8	602[5] Comp. II	4–4.5	17[6]	±3[7]
Silver copper lead pipes	Ag 0.003–0.005 Cu 0.003–0.005	1085[5]	5	17[6]	±4.2[9]
C. Lead alloys for cable sheathing					
	Sb 0.85	801 Alloy B	6–15 (depending on heat treatment)	31[6]	±8.3[7]
	Cd 0.075 Sn 0.2	801 Alloy ½ C			±3.8[7]
	Sb 0.4 Sn 0.2	801 Alloy E	6	18.5[6]	±6.6[7]

Notes:
(1) Data from BS 334 Revision–Draft for Public Comment.
(2) Rate of testing: 0.4 mm mm^{-1} min^{-1}.
(3) 20×10^6 cycles.
(4) Although no longer in commercial production in the UK, these materials are included for their scientific interest.
(5) This information is correct at time of writing, but the standards listed are shortly due for revision.
(6) Testing rate: 0.1–0.25 mm mm^{-1} min^{-1}.
(7) 10^7 cycles.
(8) Although not included in the current BS 1178, it is now generally recommended to add 0.02–0.06% copper to improve fatigue properties.
(9) 2.5×10^7 cycles.

Table 22.17 IMPORTANT LEAD ALLOYS WITH UNSPECIFIED MECHANICAL PROPERTIES[1]

Main application	*Nominal composition %*	*Specification* (BS)	*Specific use*
Soldering	Sn 64 or 60	219 Grades A, AP, K, KP	Electrical and electronics
	Sn 40, 45, 50, 60	219 Grades G, R, F, KP	Can soldering, general engineering
	Sn 30, 35	219 Grades J, H	Cable sheaths
	Sn 15, 20	219 Grades W, V	Lamps, low service temperatures
	Sn 40	219	Heat exchangers, general
	Sb 2.2	Grade C	dip soldering
	Sn 30, 32	219	Plumbing, wiped joints
	Sb 1.6, 1.8	Grades D, L	
	Sn 28, 30	AU 90	General body soldering
	Sb 1.5, 1.6	Nos. 28A, 30A	
	Sn 25	AU 90	Radiator core dipping
	Sb 1.4	No. 25A	
	Sn 16, 18, 22	AU 90	Body soldering,
	Sb 2.5, 1.0, 1.2	Nos. 16AX, 19A, 22A	radiator dipping
	Sn 5.0	AU 90	Hot dip coating, tubular
	Sb 4.0	No. 5AX	radiator manufacture
	Sn 2.6, 10.2	AU 90	Body solders for shallow
	Sb 5.1, 4.0	Nos. 3AX§, 10AX§	areas
	As 0.5		
Printing			
	Sn 2–4	—	Electrobacking metal
	Sb 2–5		
	Sn 2–5	—	Slug casting metal
	Sb 10–13		
	Sn 5–10	—	Stereotype metal
	Sb 15		
	Sn 6–13	—	Monotype casting metal
	Sb 15–19		
	Sn 13–22	—	Cast type casting metal
	Sb 20–28		

Notes:

(1) In many uses of lead alloys, the strength, hardness, etc. of the alloy are not of prime importance. In general soldering, for example, the geometry of the joint and the materials being joined, are of greater importance than the strength of the bulk solder. In most applications of type metals, fluidity of the liquid alloy, contraction properties, and wear resistance of the solid alloy, are the most important characteristics in formulating an alloy. See also Chapter 34.

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22.4 Mechanical properties of magnesium and magnesium alloys

Table 22.18 MAGNESIUM AND MAGNESIUM ALLOYS (WROUGHT) – TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

			Specifications				*Tension*			*Compression*	
Material	*Nominal* composition %*	*Form*	DTD or BS (Air)	BS (Gen. Eng.)	ASTM	*Elektron*	*Proof stress 0.2%* MPa	*UTS* MPa	*Elong.* %	*Proof stress 0.2%* MPa	*Hardness VPN* 30 kg
Mg	Mg 99.9	Sheet, annealed	–				69	185	4	–	30–35
		Bar, extruded	–				100	232	6	–	35–45
Mg–Mn	Mn 1.5	Sheet	118C	3370-MAG-S-101M	–	AM503	100	232	6	–	35–45
		Extruded bar (1 in diam.)	142B	3373-MAG-E-101M	M1A-F, B107		162	263	7	124	45–55
		Extruded tube	737A	3373-MAG-E-101M	M1A, B107		154	247	6	–	45–55
Mg–Al–Zn	Al 3.0	Sheet, annealed		3370-MAG-S-1110	AZ31, B90	AZ31	131	232	13	–	50–60
	Zn 1.0	half hard		3370-MAG-S-111M	AZ31, B90		170	263	10	100	55–70
	Mn 0.3	Extruded bar and sections		3373-MAG-E-111M	AZ31, B107		162	255	11	93	50–60
	Al 6.0	Forgings	2L513	3372-MAG-F-121M	AZ61, B91	AZM	183	293	8	147	60–70
	Zn 1.0	Extruded bar and sections	2L512	3373-MAG-E-121N	AZ61, B107		183	293	8	147	55–70
	Mn 0.3	Extruded tube	2L503	3373-MAG-E-121M	AZ61, B107		170	278	8	147	60–70
	Al 8.0	Forgings	88C	–	AZ80A, B91	AZ855	208	293	8	185	65–75
	Zn 0.5										
	Mn 0.3										
Mg–Zn–Mn	Zn 2.0	Sheet, annealed	5091	3370-MAG-S-1310		ZM21	131	232	13		
	Mn 1.0	half breed	5101	3370-MAG-S-131M			170	263	10		
		Extruded bar sections	–	3373-MAG-E-131M			162	255	11		
Mg–Zn–Zr	Zn 1.0	Sheet	2L514	3370-MAG-S-141M	–	ZW1	178	263	10	154	55–70
	Zr 0.6	Extruded bar and sections	2L508	3373-MAG-E-141M	–		208	293	13	177	60–75
		Extruded tube	2L509	3373-MAG-E-141M	–		193	278	7	–	60–75
	Zn 3.0	Sheet	2L504	3370-MAG-S-151M	–	ZW3	185	270	8	154	60–70
	Zr 0.6	Forgings	2L514	3372-NAG-F-151M	–		224	309	8	193	60–80
		Extruded bar and sections (1 in diam.)	2L505	3373-MAG-E-151M	–		239	309	18	213	65–75
	Zn 5.5	Bars and sections									
	Zr 0.6	Heat treated	5041A	3373-MAG-E-161TE	ZK60A-T5, B107-70	ZW6	270	340	10	255	60–80

continued overleaf

Table 22.18 MAGNESIUM AND MAGNESIUM ALLOYS (WROUGHT) – TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

Material	*Nominal* composition* %		*Form*	*Specifications* DTD or BS (Air)	BS (Gen. Eng.)	ASTM	*Elektron*	*Tension* *Proof stress* 0.2% MPa	*UTS* MPa	*Elong.* %	*Compression* *Proof stress* 0.2% MPa	*Hardness VPN* 30 kg
Mg–Zn–Cu–Mn	Zn	6.5	Bars and sections									
	Cu	1.3	Heat treated	–	–	ZC71-T6, B107	ZC71	340	360	6	–	–
	Mn	0.8										
Mg–Th–Zn–Zr**	Th	0.8	Extruded bar and sections 5111	–	–	–	ZTy	147	263	18	–	50–70
(Creep resistant)	Zn	0.5	Forgings 5111	–	–	–		147	232	13	–	50–70
	Zr	0.6										
Mg–Th–Mn**	Th	2.0	Sheet	–	–	HM21-T8, B90	–	165	247	9	179	–
(Creep resistant)	Mn	0.75										
	Th	3.0	Extruded bar and sections	–	–	HM31-T5	–	227	287	8	185	–
	Mn	1.2										

Nuclear alloys: Two wrought magnesium alloys (Magnox AL80; Mg0.75Al-0.005 Be and MN70; Mg0.75 Mn) of interest only for their nuclear and high-temperature properties have room-temperature tensile properties similar to those of AM503.

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance. M = As manufactured. O = Fully annealed. TE = Precipitation treated.

**Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 22.19 MAGNESIUM AND MAGNESIUM ALLOYS (CAST) TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

				Specifications				*Tension*			*Compression*	
Material	*Nominal* composition %*		*Condition*	DTD or BS (Air)	BS (Gen. Eng.)	ASTM	*Elektron*	*Proof stress* 0.2% MPa	*UTS* MPa	*Elong.* %	*Proof stress* 0.2% MPa	*Brinell hardnesst VPN* 30 kg
Mg–Zr	Zr	0.6	AC	–	–	KIA, B80	ZA	51	185	2.0	54	40–50
Mg–Al–Zn	Al	6.0	AC	–	–	AZ63A-F, B80	–	97	199	5	97	50
	Zn	3.0	TB	–	–	AZ63A-T4, B80		97	275	10	97	55
			TF	–	–	AZ63A-T6, B80		131	275	5	131	73
	Al	8.0	AC	–	2970 MAG 1-M		A8	86	158	4	86	50–60
	Zn	0.4	TB	3L122	2970 MAG 1-TB	AZ81A-T4, B80		82	247	11	82	50–60
	Al	9.5	AC	–	2970 MAG 3-M	AZ91C-F, B80	AZ91	93	154	2	93	55–65
	Zn	0.4	TB	3L124	2970 MAG 3-TB	AZ1C-T4, B80		90	232	6	90	55–65
			TF	3L125	2970 MAG 3-TF	AZ91C-T6, B80		127	239	2	124	75–85
			Die cast	–	–	AZ91B-F, B94		111	216	3	108	60–70
	Al	9.0	AC	–	–	AZ92A, B80	–	97	165	2	97	65
	Zn	2.0	TB	–	–	–		97	275	8	97	63
			TF	–	–	–		145	275	2	145	84
Mg–Zn–Zr	Zn	4.5	TE	2L127	2970 MAG 4-TE	ZK51A-T5, B80	Z5Z	161	263	6	162	65–75
	Zr	0.7										
Mg–Zn–RE–Zr	Zn	4.0	TE	2L128	2970 MAG 5-TE	ZE41A-T5, B80	RZ5	150	216	5	139	55–75
	RE	1.2										
	Zr	0.7										
	Zn	6.0	TF§	5045	–		ZE63	190	295	7	190	70–80
	RE	2.5										
	Zr	0.7										
Mg–RE–Zn–Zr (Creep resistant to 250 °C)	RE	2.7	TE	2L126	2970 MAG 6-TE	EZ33A-T5, B80	ZRE1	95	162	4.5	93	50–60
	Zn	2.2										
	Zr	0.7										
Mg–Th–Zn–Zr** (Creep resistant to 350 °C)	Th	3.0	TE	5005A	2970 MAG 8-TE	HZ32A-T5, B80	ZT1	93	216	7	93	50–60
	Zn	2.2										
	Zr	0.7										
Mg–Zn–Th–Zr**	Zn	5.5	TE	5015A	2970 MAG 9-TE	ZH62A-T5, B80	TZ6	167	270	8	162	65–75
	Th	1.8										
	Zr	0.7										

continued overleaf

Table 22.19 MAGNESIUM AND MAGNESIUM ALLOYS (CAST) TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE – *continued*

				Specifications				*Tension*			*Compression*	
Material	*Nominal* composition %*		*Condition*	DTD or BS (Air)	BS (Gen. Eng.)	ASTM	*Elektron*	*Proof stress* 0.2% MPa	*UTS* MPa	*Elong.* %	*Proof stress* 0.2% MPa	*Brinell hardnesst VPN* 30 kg
Mg–Th–Zr**	Th	3.0	TF	–	–	HK31A-T6, B80	MTZ	93	208	5	93	50–60
	Zr	0.7										
Mg–Ag–RE‡-Zr	Ag	2.5	TF	5025A	–		MSR-A	187	247	5	178	65–80
	RE	2.0‡		5035A	2970 MAG 12-TF		MSR-B	204	260	3	193	65–80
	Zr	0.6										
	Ag	2.5	TF	5055	–	QE22A-T6, B80	QE22	200	260	4	195	65–80
	RE	2.0‡										
	ZR	0.6										
Mg–RE(D)–Ag–Zr-Cu	RE(D)	2.2	TF	5055	2970 MAG 13-TF	EQ21A-T6, B80	EQ21	195	261	4	–	75–90
	Ag	1.5										
	Zr	0.6										
	Cu	0.07										
Mg–Ag–Th–RE‡Zr**	Ag	2.5	TF	–	–	QH21A-T6, B80	QH21A	210	270	4	200	65–80
	RE	1.0‡										
	Th	1.0										
Mg–Y–RE(Δ)–Zr	Y	4.0	TF	–	–	WE43-T6, B80	WE43	185	265	7	–	75–90
	Zr	0.7										
	RE(Δ)	3.4										
	Zr	0.6										
	Y	5.1	TF	–	2970 MAG 14-TF	WE54-T6, B80	WE54	205	280	4	–	75–90
	RE(Δ)	3.0										
	Zr	0.6										
Mg–Zn–Cu–Mn	Zn	6.0	TF	–	–	ZC63-T6, B80	ZC63	158	242	4.5	–	55–65
	Cu	2.7										
	Mn	0.5										

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance. RE = Cerium mischmetal containing approx. 50% cerium. RE(Δ) = Neodymium plus Heavy Rare Earth metals.
†Brinell tests with 500 kg on 10 mm ball for 30 s. RE(D) = Neodymium enriched mischmetal.
‡Fractionated rare earth metals: MSR-A contains 1.7%; MSR-B contains 2.5%.
§Solution heat treated in an atmosphere of hydrogen.
AC = Sand cast. TE = Precipitation heat treated.
TB = Solution heat treated. TF = Fully heat treated.
**Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 22.20 MAGNESIUM AND MAGNESIUM ALLOYS (EXCLUDING HIGH TEMPERATURE ALLOYS FOR WHICH SEE TABLE 22.21) – TYPICAL TENSILE PROPERTIES AT ELEVATED TEMPERATURES

				'Short-time' tension†			
Material	*Nominal composition** %	*Form and condition*	*Test temp.* °C	*Young's modulus* GPa	*0.2% proof stress* MPa	*UTS* MPa	*Elong.* %
Mg	Mg 99.95	Forged	20	45	–	170	5
			100	–	–	128	8
			150	–	–	93	16
			200	–	–	54	43
Mg–Al–Zn	Al 8.0	Sand cast	20	45	86	158	4
	Zn 0.4		100	34	76	154	5
	(A8)		150	32	65	145	11
			200	25	62	100	20
			250	–	–	75	27
		Sand cast	20	45	82	247	11
		and	100	34	73	202	16
		solution	150	33	65	154	21
		treated	200	28	62	116	25
			250	–	–	85	21
	(AZ855)	Forged	20	45	221	309	8
			150	–	153	216	25
			200	–	102	154	28
	Al 9.5	Sand cast	20	45	93	154	2
	Zn 0.4		100	–	–	131	2
	(AZ91)		150	–	–	122	6
			200	–	–	108	25
			250	–	–	77	34
		Sand cast	20	45	90	232	6
		and	100	–	–	222	12
		solution	150	–	–	196	16
		treated	200	–	–	139	20
		Sand cast	20	45	127	239	2
		and	100	40	91	232	6
		fully heat	150	37	77	185	25
		treated	200	28	62	133	34
			250	19	46	103	30
Mg–Zn–Zr	Zn 4.5	Sand cast	20	45	161	263	6
	Zr 0.7	and heat	100	34	124	185	14
	(Z5Z)	treated	150	28	102	145	20
			200	22	79	113	23
			250	19	57	85	20
	Zn 3.0	Extruded	20	45	255	309	18
	Zr 0.6		100	40	162	182	33
	(ZW3)		200	22	46	127	56
			250	12	11	100	71
		Sheet	20	45	195	270	10
			100	40	120	165	33
			150	33	74	116	42
			200	–	–	76	51
			250	–	–	49	59
Mg–Zn–RE–Zr	Zn 4.0	Sand cast	20	45	150	216	4
	Re 1.2	Sand cast	20	41	134	195	6
	Zr 0.7	treated	150	40	120	167	19
	(RZ5)		200	38	99	131	29
			250	33	74	99	35

continued overleaf

Table 22.20 MAGNESIUM AND MAGNESIUM ALLOYS (EXCLUDING HIGH TEMPERATURE ALLOYS FOR WHICH SEE TABLE 22.21) – TYPICAL TENSILE PROPERTIES AT ELEVATED TEMPERATURES – *continued*

Material	*Nominal composition** %	*Form and condition*	*Test temp.* °C	*'Short-time' tension*† *Young's modulus* GPa	*0.2% proof stress* MPa	*UTS* MPa	*Elong.* %
Mg–Zn–Th–Zr**	Zn 5.5	Sand cast	20	45	161	270	9
	Th 1.8	and heat	100	34	134	224	22
	Zr 0.7	treated	150	31	110	178	26
	(TZ 6)		200	28	82	130	26
			250	26	52	91	25
Mg–Ag–	Ag 2.5	Sand cast	20	45	201	259	4
RE–Zr	RE(D)2.0	and fully	100	41	185	232	12
(D)	Zr 0.6	heat	150	40	171	210	16
	(QE22)	treated	200	38	154	185	20
			250	34	102	142	27
			300	31	68	88	59
Mg–RE(D)–	Re(D) 2.2	Sand cast	20	45	195	261	4
Ag–Zr–Cu	Ag 1.5	and fully	100	43	189	230	10
	Zr 0.6	heat	150	42	180	211	16
	Cu 0.07	treated	200	41	170	191	16
	(EQ21)		250	39	152	169	15
			300	35	117	132	10
Mg–Ag–Re(D)**	Ag 2.6	Sand cast	20	45	210	270	4
Th–Zr	RE(D) 1.0	and fully	100	41	199	242	17
‡	Th 1.0	heat	150	40	190	224	20
	Zr 0.6	treated	200	38	183	205	18
	(OH21)		250	37	167	185	19
			300	33	120	131	20
Mg–Y–RE(Δ)–Zr	Y 4.0	Sand cast	20	45	185	265	7
	RE(Δ) 3.4	and fully	150	42	175	250	6
	Zr 0.6	heat	200	39	170	245	11
	(WE43)	treated	250	37	160	220	18
			300	35	120	160	40
	Y 5.1	Sand cast	20	45	205	280	4
	RE(Δ) 3.0	and fully	100	43	197	260	4.5
	Zr 0.6	heat	150	42	195	255	5
	(WE54)	treated	200	41	183	241	6.5
			250	39	175	230	9
			300	36	117	184	14.5
Mg–Zn–Cu–Mn	Zn 6.0	Sand cast	20	45	158	242	4.5
	Cu 2.7	and fully	100	–	141	215	9
	Mn 0.5	heat	150	–	134	179	14
	(Zc63)	treated	200	–	118	142	11
	Zn 6.5	Extruded	20	45	325	350	6
	Cu 1.3	and fully	100	40	206	259	16
	Mn 0.8	heat	200	32	115	163	14
	(Zc71)	treated					

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.

†In accordance with BS1094: 1943; 1 h at temperature and strain rate 0.1–0.25 in in^{-1} min^{-1}.

‡Tested according to BS4A4. RE = Cerium mischmetal containing approx. 50% Ce. RE(D) = Neodymium enriched mischmetal. RE(Δ) = Neodymium plus Heavy Rare Earth metals.

**Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 22.21 HIGH TEMPERATURE MAGNESIUM ALLOYS – TENSILE PROPERTIES AT ELEVATED TEMPERATURE

Material	*Nominal composition** %	*Form and condition*	*Test temp.* °C	*'Short-time' tension*† *Young's modulus* GPa	*0.2% proof stress* MPa	*UTS* MPa	*Elong.* %
Mg–RE–Zn	RE 2.7	Sand cast	20	45	93	162	4.5
	Zn 2.2	and heat	100	40	79	150	11
	Zr 0.7	treated	150	38	76	139	19
	(ZRE1)		200	36	74	125	26
			250	33	65	107	35
			300	28	48	85	51
			350	21	26	56	90
Mg–Th–Zr**	Th 3.0	Sand cast	20	45	93	208	4
	Zr 0.7	and fully	100	40	88	188	10
	(HK31)	heat	150	38	86	174	13
	(MTZ)	treated	200	38	85	162	17
			250	36	83	150	20
			300	34	73	136	22
			350	29	56	103	23
Mg–Th–Zn–Zr**	Th 3.0	Sand cast	20	45	93	216	9
	Zn 2.2	and heat	100	36	88	159	23
	Zr 0.7	treated	150	34	79	131	27
	(ZT1)		200	33	65	108	33
			250	33	56	90	38
			300	31	49	76	41
			350	28	45	63	34
	Th 0.8	Sheet	20	45	181	266	10
	Zn 0.5		100	41	179	224	10
	Zr 0.6		150	41	176	201	11
	(ZTY)		200	40	165	171	15
			250	40	124	134	20
			300	34	73	96	27
			350	29	17	56	38
Mg–Ag–RE(D)–Zr	Ag 2.5 RE(D) 2.0 Zr 0.6 (QE22)	Sand cast and fully heat treated					
Mg–RE(D)–Ag–Zr–Cu	RE(D)2.2 Ag 1.5 Zr 0.6 Cu 0.07 (EQ21)	Sand cast and fully heat treated					
Mg–Ag–RE(D)–Th–Zr**	Ag 2.5 RE(D)1.0 Th 1.0 Zr 0.6 (QH21)	Sand cast and fully heat treated		High strength cast alloys with good elevated temperature properties – for which *see* Table 22.20			
Mg–Y–RE(Δ)–Zr	Y 4.0 RE(Δ) 3.4 (WE43)	Sand cast and fully treated					
	Y 5.1 RE(Δ) 3.0 Zr 0.6 (WE54)	Sand cast and fully eat treated					

*It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.
†In accordance with BS 1094: 1943; 1 h at temperature; strain rate 0.1–0.25 in in^{-1} min^{-1}.
RE = Cerium mischmetal containing approx. 50% Ce. RE(D) = neodymium-enriched mischmetal.
RE(Δ) = Neodymium plus Heavy Rare Earths.
**Thorium containing alloys are being replaced by alternative Mg alloys.

Table 22.22 HIGH-TEMPERATURE MAGNESIUM ALLOYS – LONG-TERM CREEP RESISTANCE

Material	*Nominal composition %*	*Form and Condition*	*Temp. °C*	*Time*† *h*	*Stress to produce specified creep strains%* 0.05 MPa	0.1 MPa	0.2 MPa	0.5 MPa	1.0 MPa
Mg–RE–Zn–Zr	RE 2.7 Zn 2.2 Zr 0.7 (ZRE1)	Sand cast and heat treated	200	100	52	66	71	–	–
				500	41	54	65	–	–
				1000	36	47	58	–	–
			250	100	23	28	32	36	–
				500	11	19	24	30	34
				1000	–	14	20	26	30
			315	100	5.6	7.4	8	–	–
				500	–	5.2	6.5	–	–
				1000	–	4.3	5.6	–	–
	Zn 4.0 RE 1.2 Zr 0.7 (RZ5)	Sand cast and heat treated	100	100	–	97	111	117	–
				500	–	–	106	117	–
				1000	–	–	103	116	–
			150	100	77	86	97	101	107
				500	–	75	88	96	100
				1000	–	70	83	91	97
			200	100	29	43	52	67	73
				500	22	28	37	52	64
				1000	20	23	31	43	53
			250	100	6.2	12	19	32	39
				500	4.3	6.2	8.6	15	19
				1000	3.9	5.4	6.9	12	15
Mg–Th–Zr**	Th 3.0 Zr 0.7 (HK31) (MTZ)	Sand cast and fully heat treated	200	100	31*	45*	63*	97*	111*
				1100	–	–	62*	100*	–
			260	100	–	28*	43*	65*	–
				1000	–	–	29*	45*	–
			315	100	9.3*	14*	19*	27*	32*
Mg–Th–Zn–Zr**	Th 0.8 Zn 0.5	Sheet	250	100	Stress of 46 MPa (3 tonf in^{-2}) produced 0.03% creep strain				
	Zr 0.6 (ZTY)				Stress of 46 MPa (3 tonf in^{-2}) produced 0.03% creep strain				
Mg–Th–Zn–Zr*	Th 3.0 Zn 2.2 Zr 0.7 (ZT1)	Sand cast and heat treated	250	100	42	50	56	63	66
				500	35	43	51	58	63
				1000	31	39	48	56	61
			300	100	23	28	35	46	52
				500	19	21	25	36	41
				1000	17	19	21	32	36
			325	100	14	19	24	29	36
				500	12	13	16	21	25
				1000	10	12	13	15	20
			350	100	10	12	18	21	23
				500	–	9	10	12	14
				1000	–	8	8	9	10
			375	100	–	8	11	12	13
				500	–	–	–	8	9
				1000	–	–	–	–	8
	Zn 5.5 Th 1.8 Zr 0.7 (TZ6)	Sand cast and heat treated	150	100	51	66	82	96	102
				500	36	56	69	85	94
				1000	26	51	63	80	90
			200	100	26	32	45	56	62
				500	15	22	26	40	49
				1000	11	17	20	31	40

Table 22.22 HIGH-TEMPERATURE MAGNESIUM ALLOYS – LONG-TERM CREEP RESISTANCE – *continued*

Material	*Nominal composition %*	*Form and Condition*	*Temp. °C*	*Time*† *h*	*Stress to produce specified creep strains%* 0.05 MPa	0.1 MPa	0.2 MPa	0.5 MPa	1.0 MPa
Mg–Ag–RE(D)–Zr	Ag 2.5 RE(D) 2.0 Zr 0.6 (QE22)	Sand cast and fully heat treated	200	100	55	74	88	–	–
				500	–	54	65	82	89
				1000	–	46	56	73	79
			250	100	18	26	33	–	–
				500	–	15	22	28	31
				1000	–	10	16	22	26
Mg–RE(D)–Ag–Zr–Cu	RE(D) 2.2 Ag 1.5 Zr 0.6 Cu 0.07 (EQ21)	Sand cast and fully heat treated	200	100	–	78	95	116	–
				500	–	57	71	88	–
				1000	–	48	62	76	–
			250	100	–	29	36	42	–
				500	–	18	22	30	–
				1000	–	14	19	24	–
Mg–Ag–RE(D)–Th–Zr**	Ag 2.5 RE(D) 1.0 Th 1.0 Zr 0.6 (QH21)	Sand cast and fully heat treated	250	100	22	32	39	–	–
				500	–	20	26	32	36
				1000	–	–	21	26	30
Mg–Y–RE(Δ)–Zr	Y 4.0 RE(Δ) 3.4 Zr 0.6 (WE43)	Sand cast and fully heat treated	200	100	–	148	161	173	–
				500	–	–	115	148	–
				1000	–	–	96	139	–
			250	100	–	44	61	–	–
				500	–	–	46	–	–
				1000	–	–	39	–	–
	Y 5.1 RE(Δ) 3.0 Zr 0.6 (WE54)	Sand cast and fully heat treated	200	100	–	160	165	–	–
				500	–	120	140	–	–
				1000	–	120	132	–	–
			250	100	–	47	61	81	–
				500	–	43	40	58	–
				1000	–	16	32	48	–
Mg–Zn–Cu–Mn	Zn 6.0 Cu 2.7 Mn 0.5 (ZC63)	Sand cast and fully heat treated	150	100	–	94	99	104	–
				500	–	82	92	98	–
				1000	–	74	89	95	–
			200	100	–	60	63	67	–
				500	–	51	55	61	–
				1000	–	42	49	55	–

*Total strains.
†4–6 h heating to test temperature followed by 16 h soaking at test temperature.
RE = Cerium mischmetal containing approx. 50% Ce.
RE(D) = Neodymium-enriched mischmetal.
RE(Δ) = Neodymium plus Heavy Rare Earth metals.
**Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 22.23 HIGH-TEMPERATURE MAGNESIUM ALLOYS – SHORT-TERM CREEP RESISTANCE

Material	*Nominal composition %*	*Form and condition*	*Temp. °C*	*Time*† *s*	*Stress to produce specified creep strains%* 0.05 MPa	1.0 MPa	2.0 MPa	5.0 MPa	10.0 MPa	*Stress to fracture* MPa
Mg–RE–Zn–Zr	Re 2.7 Zn 2.2 Zr 0.7 (ZRE1)	Sand cast and heat treated	200	30	–	–	98	118	130	136
				60	–	–	97	117	128	134
				600	–	–	96	116	125	129
			250	30	76	84	92	111	123	130
				60	74	83	91	110	120	129
				600	73	82	89	108	114	125
			315	30	52	59	73	80	85	90
				60	51	58	69	76	83	88
				600	42	49	56	62	68	73
	Zn 4.0 RE 1.2 Zr 0.7 (RZ5)	Sand cast and heat treated	200	30	100	107	116	127	–	136
				60	99	105	114	124	–	134
				600	86	99	103	114	–	125
			250	30	86	90	94	99	–	116
				60	83	88	91	96	–	113
				600	71	76	81	86	–	93
			315	30	62	69	76	79	83	86
				60	59	66	73	76	79	82
				600	48	53	59	64	67	69
Mg–Th–Zr*	Th 3.0 Zr 0.7 (HK31) (MTZ)	Sand cast and fully heat treated	250	30	96	103	119	138	–	145
				60	95	103	118	137	–	145
				600	94	102	117	137	–	144
			315	30	80	88	103	117	–	128
				60	78	86	102	116	–	127
				600	74	82	96	107	–	120
Mg–Th–Zn–Zr*	Th 0.8 Zn 0.5 Zr 0.6 (ZTY)	Sheet	250	30	–	–	110	159	163	165
				60	–	–	95	157	160	162
				600	–	–	–	145	149	151
			350	30	20	32	48	80	93	102
				60	18	28	40	67	82	98
				600	–	15	20	31	42	66
Mg–Th–Zn–Zr*	Th 3.0 Zn 2.2 Zr 0.7 (ZT1)	Sand cast and heat treated	200	30	–	–	–	100	118	125
				60	–	–	–	96	114	123
				600	–	–	–	85	103	114
			250	30	58	65	71	84	102	111
				60	57	64	69	81	99	107
				600	56	63	68	74	86	98
			315	30	55	60	64	73	76	82
				60	53	59	63	72	76	80
				600	50	59	61	71	74	77
	Zn 5.5 Th 1.8 Zr 0.7 (TZ6)	Sand cast and heat treated	200	30	96	113	120	128	137	144
				60	93	109	117	124	133	137
				600	63	90	102	110	114	119
			250	30	70	77	85	96	99	107
				60	65	74	80	90	94	99
				600	56	60	66	74	77	82
			315	30	54	59	64	70	74	76
				60	52	57	62	66	70	73
				600	44	49	53	56	58	59

† 1 h heating to test temperature followed by 1 h soaking at test temperature.
RE = cerium mischmetal containing approx. 50% Ce.
*Thorium-containing alloys are being replaced by alternative Mg alloys.

Table 22.24 MAGNESIUM AND MAGNESIUM ALLOYS – FATIGUE AND IMPACT STRENGTHS

					Fatigue strength† *at specified cycles*						*Impact strength*§ *for single blow fracture*		
Material	*Nominal composition** %	*Condition*	‡ *State*	*temp.* °C	10^5 MPa	5×10^5 MPa	10^6 Mpa	5×10^6 MPa	10^7 MPa	5×10^7 MPa	*Test temp.* °C	*Unnotched* J	*Notched* J
Mg–Mn	Mn 1.5 (AM503)	Extruded	U	20	107	90	88	86	85	83	20	12–14	4–4.5
			N		76	90	54	51	50	48			
Mg–Al–Zn	Al 6.0 Zn 1.0 (AZM)	Extruded	U	20	161	139	133	125	124	120	20	34–43	7–9.5
			N		127	110	103	97	94	91			
	Al 8 Zn 0.4 (A8)	Sand cast	U	20	108	93	90	88	88	86	20	3–5	1.5–2
			N		107	80	73	66	65	63			
		Sand cast and solution treated	U	20	124	102	97	91	90	90	20	18–27	4.5–7
			N		108	86	82	74	73	69			
			U	150	93	69	66	59	57	57			
			U	200	71	52	48	38	36	31	−196	1.5	
	Al 9.5 Zn 0.4 (AZ91)	Sand cast	U	20	114	91	89	88	86	85	20	1.5–2.0	1–1.5
			N		110	83	74	68	66	63			
		Sand cast and solution treated	U	20	124	93	93	93	93	–	20	7–9.5	3–4
			N		103	82	80	79	79	77			
		Sand cast and fully heat treated	U	20	117	90	80	79	77	76	20	3–4	1–1.5
			N		93	66	66	65	65	65			
Mg–Zn–Zr	Zn 3.0 Zr 0.6 (ZW3)	Extruded	U	20	151	137	134	128	127	124	20	23–31	9.5–12
			N		124	99	93	91	90	88			
	Zn 4.5 Zr 0.7 (Z5Z)	Sand cast and heat treated	U	20	111	86	85	82	80	77	20	7–12	3–4
			N		90	86	85	82	80	77	−196	0.8	
Mg–Zn–RE–Zr	Zn 4.0 RE 1.2 Zr 0.7 (RZ5)	Sand cast and heat treated	U	20	124	99	97	97	96	94	20	4–5.5	1–2
			N		108	93	91	88	86	83	−196	0.7	
			U	150	97	85	80	73	69	65			
			U	200	93	74	69	62	59	54			

continued overleaf

Table 22.24 MAGNESIUM AND MAGNESIUM ALLOYS – FATIGUE AND IMPACT STRENGTHS – *continued*

Material	*Nominal* composition* %	*Condition*	‡ *State*	*temp.* °C	*Fatigue strength† at specified cycles*						*Impact strength§ for single blow fracture*		
					10^5 MPa	5×10^5 MPa	10^6 Mpa	5×10^6 MPa	10^7 MPa	5×10^7 MPa	*Test temp.* °C	*Unnotched* J	*Notched* J
	Zn 2.2 RE 2.7 Zr 0.7 (ZRE1)	Sand cast and heat treated	U	20	100	82	80	79	77	74	20	6–7.5	1–2
			N		77	59	54	52	52	51			
			U	150	69	60	59	57	57	57			
			U	200	68	59	56	52	51	51			
			U	250	59	48	45	43	43	42	−196	0.5	
			U	300	49	39	37	37	36	34			
	Zn 6 RE 2.5 Zr 0.6 (ZE63)	Sand cast and fully heat treated**	U	20	144	131	127	121	119	117	20	12.9–17.6	2.3–2.7
			N		99	83	79	73	72	71			
Mg–Ag–RE(D)–Zr	Ag 2.5 RE(D) 2.5 Zr 0.6 (MSR–B)	Sand cast and fully heat treated	U	20	119	103	103	103	102	100			
			N		77	65	63	62	62	62			
			N	200	–	–	–	90	88	86			
			U	250	–	77	68	57	54	51			
Mg–Ag–RE(D)Th–Zr**	Ag 2.5 Re(D) 1.0 Th 1.0 Zr 0.6 (QH21)	Sand cast and fully heat treated	U	20	135	114	111	109	108	108			
			N		86	72	69	64	63	62			
			U	250	108	76	65	56	55	52			
Mg–Zn–Th–Zr**	Zn 5.5 Th 1.8 Zr 0.7 (TZ6)	Sand cast and heat treated	U	20	120	86	85	83	83	82	20	8–11	1.5–3
			N		100	86	80	77	76	76	−196	0.5	
Mg–Th–Zr**	Th 3.0 Zr 0.7 (MTZ)	Sand cast and fully heat treated	U	20	–	74	68	65	63	62			
			N		–	48	40	36	34	32			
			U	200	–	74	68	60	59	58			
			U	250	80	63	59	54	52	51			

Mg–Th–Zn–Zr***	Th	0.7	Extruded	U	20	100	86	83	79	76	74			
	Zn	0.5		N		73	52	51	49	48	46			
	Zr	0.6		U	200	–	74	68	60	59	57			
	(ZTY)			U	250	80	63	59	54	52	51			
	Th	3.0	Sand cast and	U	20	97	82	79	74	71	68	20	7–8	1.5–3
	Zn	2.2	heat treated	N		76	59	56	51	49	48			
	Zr	0.7		U	200	71	60	59	54	52	51			
	(ZT1)			U	250	66	51	46	43	42	39			
				U	325	–	–	43	37	34	29	−196	0.8	
Mg–RE(D)–As–Zr–Cu	RE(D)	2.2	Sand cast and	U	20	103	94	93	92	91	90			
	Ag	1.5	fully heat											
	Zr	0.6	treated											
	Cu	0.07												
Mg–Y–RE(Δ)–YZr	Y	4.0	Sand cast and	U	20	114	101	98	94	93	91			
	RE(Δ)	3.4	fully heat	U	150	107	97	94	87	85	83			
	Zr	0.6	treated	U	250	107	81	74	65	64	62			
	Y	5.9	Sand cast and	U	20	113	104	102	100	99	97			
	RE(Δ)	3.0	fully heat	U	200	118	96	90	84	83	82			
	Zr	0.6	treated	U	250	115	84	78	67	66	65			
Mg–Zn–Cu–Mn	Zn	6.0	Sand cast and	U	20	–	–	100	94	92	90			
	Cu	2.7	fully heat	N		–	–	62	57	56	55			
	Mn	0.5	treated											

* It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.
**Solution heat treated in an atmosphere of hydrogen.
† Wohler rotating beam tests at 2960 c.p.m.
‡ U = Unnotched.
N = Notched. Semi-circular notch of 0.12 cm (0.047 in) radius. Stress concentration factor 1.8.
§ Hounsfield balanced impact test, notched bar values are equivalent to Izod values.
RE(D) = Neodymium enriched mischmetal.
***Thorium-containing alloys are being replaced by alternative Mg alloys.
RE(Δ) = Neodymium plus Heavy Rare Earths.

Table 22.25 HEAT TREATMENT OF MAGNESIUM ALLOY CASTINGS

Heat treatment conditions for magnesium sand castings can be varied depending on the particular components and specific properties required. The following are examples of the conditions used for each alloy which will give properties meeting current national and international specifications.

Material		*Nominal* composition* %		*Condition*	*Time* h	*Temperature* °C
Mg–Al–Zn	(AZ80)	Al	8.0	TB	12–24	400–420
		Zn	0.4			
	(AZ91)	Al	9.5	TB	16–24	400–420
		Zn	0.4			
	(AZ91)			TF	16–24	400–420
						Air cool
					8–16	180–210
Mg–Zn–Zr	(ZSZ)	Zn	4.5	TE	10–20	170–200
		Zr	0.7			
Mg–Zn–RE–Zr	(RZ5)	Zn	4.0	TE	2–4	320–340
		RE	1.2			Air cool
		Zr	0.7		10–20	170–200
	(ZRE1)	RE	2.7	TE	10–20	170–200
		Zn	2.2			
		Zr	0.7			
Mg–Th–Zr†	(HK31)	Th	3.0	TF	2–4	560–570
		Zr	0.7			Air cool
					10–20	195–205
Mg–Zn–Th–Zr†	(TZ6)	Zn	5.5	TE	2–4	320–340
		Th	1.8			Air cool
		Zr	0.7		10–20	170–200
	(ZT1)	Th	3.0	TE	10–20	310–320
		Zn	2.2			
		Zr	0.7			
Mg–Ag–RE(D)Zr	(QE22)	Ag	2.5	TF	4–12	520–530
		RE(D)	2.0		Water/Oil Quench	
		Zr	0.6		8–16	195–205
Mg–RE(D)–Ag–Zr–Cu	(EQ21)	RE(D)	2.2	TF	4–12	515–525
		Ag	1.5		Water/Oil Quench	
		Zr	0.6		12–16	195–205
		Cu	0.07			
Mg–Ag–RE(D)–Th–Zr	(QH21)†	Ag	2.5	TF	4–12	520–530
		RE(D)	1.0		Water/Oil Quench	
		Th	1.0		12–20	195–205
		Zr	0.6			
Mg–Y–RE(Δ)–Zr	(WE43)	Y	4.0	TF	4–12	520–530
		RE(Δ)	3.4		Water/Oil Quench	
		Zr	0.6		12–20	245–255
	(WE54)	Y	5.1	TF	4.12	520–530
		RE(Δ)	3.0		Water/Oil Quench/Air Cool	
		Zr	0.6		12–20	245–255
Mg–Zn–Cu–Mn	(ZC63)	Zn	6.0	TF	4–12	435–445
		Cu	2.7		Water Quench	
		Mr	0.5		16–24	180–200

* It is usual to add 0.2–0.4% Mn to alloys containing aluminium to improve corrosion resistance.
RE = Cerium mischmetal containing approximately 50% cerium.
RE(D) = Neodymium-enriched mischmetal.
RE(Δ) = Neodymium plus Heavy Rare Earth metals.
TB = Solution heat treated.
TE = Precipitation heat treated.
TF = Fully heat treated.

† Thorium-containing alloys are being replaced by alternative Mg alloys.

Note:- Above 350 °C, furnace atmospheres must be inhibited to prevent oxidation of magnesium alloys. This can be achieved either by:
(i) adding 1/2–1%SO_1 gas to the furnace atmosphere; or
(ii) carrying out the heat treatment in an atmospbere of 100% dry CO_2.

Mechanical properties at subnormal temperatures

At temperatures down to −200 °C tensile properties have approximately linear temperature coefficients: proof stress and UTS increase by 0.1–0.2% of the RT value per °C fall in temperature, and elongation falls at the same rate: modulus of elasticity rises approximately 19 MPa (2800 lbf in^{-2}) per °C over the range 0° to −100 °C. No brittle-ductile transitions have been found.

Tests at −70 °C have suggested that the magnesium-zinc-zirconium alloys show the best retention of ductility and notched impact resistance at this temperature.

22.5 Mechanical properties of nickel and nickel alloys

Table 22.26 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, STANDARD SPECIFICATIONS* AND DESIGNATIONS

Alloy	*Nominal composition* %		*France* AFNOR	*Germany* DIN	Werkstoff Nr.	*UK* BS *and* DTD	*USA* ASTM	ASME	AMS	AECMA	UNS
Nickel 200 201	Ni	99.6	–	17740; Ni 99.2 17750-4	2.406 6/2.406 0 2.406 8/2.406 1	3072-76:NA11 3072-76:NA12	B160-163 B725, B730	SB160-163	5553	–	NO2200
Nickel 205	–	99.6 min.	–	–	2.406 1		F1-3, F9	5555	–		NO2205
Monel 400	Cu Fe Mn	30 1.5 1.0	NU 30	17743: Ni Cu 30 Fe 17750 17751 17752 17753 17754	2.436 0 2.436 1	3072-76:NA13	B127 B163-165 B564	SB127 SB163-165 SB564	4544 4574 4675 4730 4731 7233	–	NO4400
Monel 450	Ni Fe Cu	31.0 0.7 Rem.	–	–	–	–	B111, B122 B151, B171 B359, B395 B432, B466-7 B543, B552	SB111, SB177 SB359, SB395 SN466, SB4467 SB543	–	–	C71500
Monel K-500	Cu Al Ti	29 2.8 0.5	–	17743:Ni Cu 30 Al 17752 17754	2.437 5	3072-76: NA 18	–	Boiler code sect. VIII	4676	–	NO5500
Inconel 600	Cr Fe	16 6	NC 15Fe	17742:Ni Cr 15 Fe 17750 17751 17752 17753 17754	2.481 6	3072-76: NA 14	B163 B166-168 B516 B517 B564 B951	SB163 SB166-168 SB564	5540 5580 5665 5687 7232	–	NO6600
Inconel 601	Ni Cr Al Fe	60.5 23.0 1.4 15.1	–	17742 17750 17751 17752	2.485 1	–	–	Boiler code VIII	5715 5870		NO6601

Table 22.26 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, STANDARD SPECIFICATIONS* AND DESIGNATIONS—*continued*

Alloy	*Nominal composition* %	*France* AFNOR	*Germany* DIN	Werkstoff Nr.	*UK* BS *and* DTD	*USA* ASTM	ASME	AMS	AECMA	UNS
Inconel 617	Ni 55.7 Cr 21.5 Co 12.5 Mo 9.0 Al 1.2 C 0.1	—	—	—	—	—	Boiler codes I and VIII	—	—	NO6617
Inconel 625	Cr 21.5 Mo 9.0 Nb 3.6	—	17744 17750 17751 17752 17754	2.4856	3072 3074 3076(NA21)	B443 B444 B446 B565 B704 B705 B751	SB443 SB444 SB446 SB564	5666 5599 5837 5581	—	NO6625
Inconel 718	Ni 52.5 Cr 19.0 Fe 18.8 Nb 5.2 Mo 3.1 Ti 0.9 Al 0.5	NC 19 Fe Nb	—	2.4668	—	B637, B670	Boiler codes I and III	—	Pr EN 2404 2405, 2407 2408, 2952 2961, 3219	NO7718
Inconel X-750	Cr 15 Fe 7 Ti 2.5 Al 0.6 Nb 0.8	NC 15Fe-T	—	2.4669	HR 505	B637	SA637	5542 5582/3 5598 5667/8/9 5670/1 568/9 5747, 7246	—	NO7750
Inconel MA 754	Ni 78.0 Cr 20.0 Fe 1.0 Y_2O_3 0.6	—	—	—	—	—	—	—	—	NO7754
INCO 330	Ni 35.5 Fe 44.8 Cr 18.5 Si 1.2	—	—	—	—	B511, B512 B535, B536 B546, B710	SB511, SB536 SB710 Boiler codes VIII, IX	5592 5716	—	NO8330

INCO 020	Ni	35.0	—		—	—	B464–4	SB462, SB464	—	—	NO8020
	Fe	38.4					B468	SB468			
	Cr	20.0					B472–4	Boiler codes			
	Cu	3.5					B751	III, VIII, IX			
	Mo	2.5									
	Nb	0.6									
INCO G-3	Ni	49.0	—	17744	2.4619	—	B581–2	SB581–2	—	—	NO6985
	Cr	22.5		17750–17752			B619, B622	SB619, SB622			
	Fe	19.5					B626, B751	SB626			
	Mo	7.0						Boiler codes			
	Cu	2.0						VIII, IX			
INCO C-276	Ni	59.0	- -	17744	2.4819	- –	B574- 5	SB574- 5	—		N10276
	Mo	16.0		17750–17752			B619, B622	SB619, SB622			
	Cr	15.5					B626, B751	SB626			
	Fe	5.5						Boiler codes			
	W	4.0						I, III, VIII, IX			
INCO-HX	Ni	48.3	NC 22 Fe D	—	2.4665	HR 6, HR 204	B435, B572	SB435, SB572		Pr EN 2182	NO6002
	Cr	22.0					B619, B622	SB619, SB622		2185	
	Fe	18.5					B626, B751	SB626			
	Mo	9.0						Boiler codes			
	Co	1.5						III, VIII, IX			
	W	0.6									
	C	0.1									
Incoloy 800	Fe	46	25 NC35-20	X10 Ni Cr Al Ti	1.4876	3072–76: NA 15	B163	SB163	5766	—	NO8800
Incoloy 800 HT	Cr	21		3220			B407–409	SB407–409	5871		NO8811
	Ti	0.4					B564	SB564			
	Al	0.4					B514-5				
							B751				
Incoloy 825	Fe	30	WFe 32C20DU	17744	2.4858	3072–76: NA 16	B163	SB163	—	—	NO8825
	Cr	21		17750–2			B423–425	SB423–425			
	Mo	3		17754			B704-5				
	Cu	2					B751				
	Ti	2									
Incoloy DS	Fe	40	—	—	—	3072–76: NA 17	—	—	—		—
	Cr	18									
	Si	2									

Table 22.26 WROUGHT NICKEL AND HIGH HICKEL ALLOYS, STANDARD SPECIFICATIONS* AND DESIGNATIONS—*continued*

Alloy	*Nominal composition* %	*France* AFNOR	*Germany* DIN	Werkstoff Nr.	*UK* BS *and* DTD	*USA* ASTM	ASME	AMS	AECMA	UNS
Ni-Span C-902	Ni 42 Fe Rem. Cr 5.5 Ti 2.5 Al 0.5	—	—	—	3127	—	—	5210 5221 5223 5225	—	NO9902
Hastelloy B–2	Mo 28	—	—	—	—	B333– B335– B619 B622	SB333 SB335 SB619 SB662	—	—	N10665
Hastelloy C–4	Mo 16 Cr 16	—	—	—	—	B574 B575 B619 B662	SB574 SB575 SB619 SB662	—	—	NO6455
Hastelloy X	Mo 9 Cr 21 Fe 18	NC 22FeD	LW2.4665	—	HR6 HR204	B435 B572 B619 B622 B626	—	5536, 5587 5754, 5588	Ni–P93–HT	NO6002
Nimonic 75	Cr 20 Ti 0.4	NC 20T	17742: Ni Cr 20 Ti LW 2.4630 17750–2	2.4951 2.4630	Hr5 HR203 HR403 HR504	—	—	—	Pr EN 2293–4 2302 2306–8 2402 2411	NO6075
Nimonic 80A	Cr 20 Ti 2.0 Al 1.5	NC 20TA	Ni Cr 20 Ti Al 17742 17754	2.4631 2.4952	3076: NA 20 HR1 HR201 HR401 HR601	B637	—	—	Pr EN 2188–91 2396 2397	NO7080
Nimonic 90	Cr 20 Co 17 Ti 2.4 Al 1.4	NCK 20TA	—	2.4632	HR2 HR202 HR402 HR501 HR502–3 BS3975–NA19	—	—	5829	Pr EN 2295–99 2401–2 2412 2669–70	NO7090

Nimonic 105	Cr 15 Co 20 Mo 5 Al 5 Ti 1.2	MK 20CDA	—	2.4634	HR3	—	—		Pr EN 2179–81	—
Nimonic 115	Cr 14 Co 13 Mo 3 Al 5 Ti 4	NK 20ATD	—	2.4636	HR4	—	—	—	Pr EN 2196 2197	—
Nimonic 263	Cr 20 Co 20 Mo 6 Ti 2 Al 0.5	NCK 20D	—	2.4650	HR10 HR206 HR404	—		5872	Pr EN 2199– 2203 2418	NO7263
Nimonic 901	Fe 35 Cr 13 Mo 6 Ti 3	Z8 NC DT 42	—	2.4662	HR53	—	—	5660 5661	Pr EN 2176–8	NO9901
Nimonic PE16	Fe 32 Cr 16 Mo 3 Ti 1.0 Al 1.0	NW 11 AC	—	—	Hr55 HR207	—	—	—	—	—
Nimonic PK33	Cr 18 Co 14 Mo 7 Ti 2.25 Al 2.1	NC 19 KDu/v		—	DTD5057	—	—	—	—	—
Astroloy	Ni 54.8 Cr 15.0 Co 17.0 Mo 5.3 Al 4.0 Ti 3.5	—	—	—	—	—	—			—

Table 22.26 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, STANDARD SPECIFICATIONS* AND DESIGNATIONS—*continued*

Alloy	*Nominal composition* %	*France* AFNOR	*Germany* DIN	Werkstoff Nr.	*UK* BS *and* DTD	*USA* ASTM	ASME	AMS	AECMA	UNS
Rene 41	Ni 55.4 Cr 19.0 Co 11.0 Mo 11.0 Al 1.5 Ti 3.1	—	—	—	—	—	—	—	—	NO7041
Rene 95	Ni 61.5 Cr 14.0 Co 8.0 Mo 3.5 Nb 3.5 Al 3.5 Ti 2.5	—	—	—	—	—	—	—	—	—
Rene 100	Ni 61.8 Cr 9.5 Co 15.0 Mo 3.0 Al 5.5 Ti 4.2 V 1.0	—	—	—	—	—	—	—	—	—
Udimet 500	Ni 53.7 Cr 18.0 Co 18.5 Mo 4.0 Al 2.9 Ti 2.9	—	—	—	—	—	—	—	—	NO7500
Udimet 700	Ni 55.5 Cr 15.0 Co 17.0 Mo 5.0 Al 4.0 Ti 3.5	—	—	—	—	—	—	—	—	—
Waspaloy	Ni 58.7 Cr 19.5 Co 13.5 Mo 4.3 Al 1.3 Ti 3.0	—	—	—	—	—	—	—	—	NO7001

* Specification constantly under review; check for latest issue.
† Association Européenne des Constructeurs de Matériel Aérospatial

Table 22.27 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, MECHANICAL PROPERTIES[1] AT ROOM TEMPERATURES

Alloy[3]	*Nominal composition* %	*Condition*	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %	*Brinell hardness*	*Izod impact* J
Nickel—pure	Ni 99.9	Annealed	60	310	40	85	160
Nickel—comc.	Ni 99.0	Annealed	150	400	40	100	160
		Hot rolled	200	500	40	120	160
		Cold drawn	480	660	25	190	—
Nickel 205	Ni 99.6 min.	Annealed	90	345	45	80	—
Monel[1] 400	Cu 31.5	Annealed	240	550	40	125	140
	Fe 1.5	Hot rolled	490	620	35	150	140
	Mn 1.0	Cold drawn	570	700	25	190	110
Monel 450	Ni 31.0	Annealed	165	385	46	90	—
	Fe 0.7						
	Cu Rem.						
Monel K-500	Cu 29	Annealed and aged	790	1 100	30	290	—
	Al 2.8						
	Ti 0.5	Hot rolled and aged	880	1 110	25	310	—
		Cold drawn and aged	850	1 110	20	310	—
Cupro-nickel[4]	Cu 55	Annealed	200	400	45	—	—
		Cold drawn	450	590	20	—	—
Inconel[1] 600	Cr 15.5	Annealed	310	655	45	150	160
	Fe 8	Cold drawn	700	880	20	200	110
Inconel 601	Ni 60.5	Annealed	210–340	550–790	70–40	110–150	—
	Cr 23.0						
	Al 1.4						
	Fe 15.1						
Inconel 617	Ni 55.7	Annealed	350	760	58	173	—
	Cr 21.5						
	Co 12.5						
	Mo 9.0						
	Al 1.2						
	C 0.1						
Inconel 625	Cr 22	Annealed	520	930	45	186	—
	Nb 4	Solution treated	352	810	50	157	—
	Mo 9						
Inconel 718	Ni 52.5	Precipitation hardened	1 180	1 350	17	382	—
	Cr 19.0						
	Fe 18.8						
	Nb 5.2						
	Mo 3.1						
	Ti 0.9						
	Al 0.5						
Inconel X-750	Cr 15	Fully heat treated	900	1 240	20	382	—
	Fe 7						
	Ti 2.5						
	Al 0.6						
	Nb 0.8						
Inconel MA 754	Ni 78.0						
	Cr 20.0						
	Fe 1.0						
	Y_2O_3 0.6						
INCO 330	Ni 35.5	Annealed	270	590	47	150	—
	Fe 44.8						
	Cr 18.5						
	Si 1.2						

Table 22.27 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, MECHANICAL PROPERTIES[1] AT ROOM TEMPERATURES—*continued*

Alloy[3]	*Nominal composition* %	*Condition*	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %	*Brinell hardness*	*Izod impact* J
INCO 020	Ni 35.0 Fe 38.4 Cr 20.0 Cu 3.5 Mo 2.5 Nb 0.6	Annealed	310	620	40	183	—
INCO G-3	Ni 49.0 Cr 22.5 Fe 19.5 Mo 7.0 Cu 2.0	Annealed	320	690	50	146	—
INCO C-276	Ni 59.0 Mo 16.0 Cr 15.5 Fe 5.5 W 4.0	Annealed	415	790	50	184	—
INCO-HX	Ni 48.3 Cr 22.0 Fe 18.5 Mo 9.0 Co 1.5 W 0.6 C 0.1	Annealed	340	790	45	184	—
Incoloy[1] 800	Fe 46 Cr 21 Ti 0.4 Al 0.4	Annealed Cold drawn	310 700	590 880	45 20	180 250	160 110
Incoloy 825	Fe 32 Cr 21 Mo 3 Cu 2 Ti 1	Annealed	340	650	40	150	160
Incoloy DS	Fe 40 Cr 18 Si 2	Annealed Cold drawn	220 850	600 1 000	61 10	190 300	140 110
Ni-Span[1] C-902	Fe 47 Cr 5.5 Ti 2.5 Al 0.5	Fully heat treated	770	1 200	25	300	—
Hastelloy B-2	Mo 28	Solution treated	526	955	53	235	—
Hastelloy C-4	Mo 16 Cr 16	Solution treated	416	768	52	184	—
Hastelloy C-276	Mo 16 Cr 15 W 4 Fe 5 C 0.02	Solution treated	360	790	60	200	160
Hastelloy X	Mo 9 Cr 21 Fe 18	Solution treated	350	800	45	175	75
Brightvay C	Cr 20 Si 1	Annealed	330	760	40	160	—
Nimonic[1] 75	Cr 20 Ti 0.4	Annealed	240	750	40	170	110
Nimonic 80A	Cr 20 Ti 2.0 Al 1.5	Fully heat treated	780	1 220	30	370	70

Table 22.27 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, MECHANICAL PROPERTIES[31] AT ROOM TEMPERATURES—*continued*

Alloy[31]	*Nominal composition* %	*Condition*	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %	*Brinell hardness*	*Izod impact* J
Nimonic 90	Cr 20 Co 17 Ti 2.4 Al 1.4	Fully heat treated	750	1175	30	380	70
Nimonic 105	Cr 15 Co 20 Mo 5 Al 5 Ti 1.2	Fully heat treated	780	1140	22	380	16
Nimonic 115	Cr 14 Co 13 Mo 3 Al 5 Ti 4	Fully heat treated	865	1240	27	400	—
Nimonic 263	Cr 20 Co 20 Mo 6 Ti 2 Al 0.5	Fully heat treated	580	970	39	320	—
Nimonic 901	Fe 35 Cr 13 Mo 6 Ti 3	Fully heat treated	900	1220	15	—	—
Nimonic PE16	Fe 32 Cr 16 Mo 3 Ti 1.0 Al 1.0	Fully heat treated	460	850	30	280	—
Nimonic PK 33	Cr 18 Co 14 Mo 7 Ti 2.2 Al 2.1	Fully heat treated	790	1170	30	—	—
Astroloy	Ni 54.8 Cr 15.0 Co 17.0 Mo 5.3 Al 4.0 Ti 3.5	Precipitation hardened	1050	1415	16	—	—
Rene 41	Ni 55.4 Cr 19.0 Co 11.0 Mo 11.0 Al 1.5 Ti 3.1	Precipitation hardened	1060	1420	14	—	
Rene 95	Ni 61.5 Cr 14.0 Co 8.0 Mo 3.5 Nb 3.5 Al 3.5 Ti 2.5	Precipitation hardened	1310	1620	15	—	
Udimet 500	Ni 53.7 Cr 18.0 Co 18.5 Mo 4.0 Al 2.9 Ti 2.9	Precipitation hardened	840	1310	32	—	

Table 22.27 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, MECHANICAL PROPERTIES[1] AT ROOM TEMPERATURES—*continued*

Alloy[3]	*Nominal composition* %	*Condition*	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %	*Brinell hardness*	*Izod impact* J
Udimet 700	Ni 55.5 Cr 15.0 Co 17.0 Mo 5.0 Al 4.0 Ti 3.5	Precipitation hardened	965	1 410	17	—	—
Waspaloy	Ni 58.5 Cr 19.5 Co 13.5 Mo 4.3 Al 1.3 Ti 3.0	Precipitation hardened	795	1 275	25	—	—

(1) Registered Trade Mark.
(2) All values in the tables in this section are representative and not to be considered as minima or maxima not to be used for specification purposes. Conversion figures have all been rounded off and are not to be taken as precise equivalents.
(3) Where trade marks apply to the name of an alloy there may be materials of similar composition available from other producers who may or may not use the same suffix along with their own trade names. The suffix alone, e.g. Alloy 800 is sometimes used as a descriptive term for the type of alloy but trade marks can be used only by the registered user of the mark.
(4) Other copper–nickel alloys, cupro-nickels, will be found listed under copper base alloys.
(5) Fully heat-treated usually implies a solution treatment followed by some form of precipitation hardening cycle. The precise heat-treatment and the associated properties may be varied to suit particular applications or according to the form of the alloy as forging, bar, sheet or welded fabrication.
(6) There are many nickel chromium alloys with and without iron used for electrical resistance heating and for general high-temperature applications in furnaces and heat-treatment plant. This alloy is typical.

Table 22.28 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, SHORT-TIME HIGH-TEMPERATURE TENSILE PROPERTIES

Alloy	*Nominal composition* %	*Condition*	*Test temperature* °C	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %
Nickel	Ni 99.0	Hot rolled	20	170	490	50
			200	150	540	50
			400	140	540	50
			600	110	250	60
			800	—	170	60
Nickel 205	Ni 99.6 min.	Annealed	20	90	345	45
Monel* 400	Cu 30 Fe 1.5 Mn 1.0	Hot rolled	20	230	560	45
			200	200	540	50
			400	220	460	52
			600	120	260	30
			800	77	120	54
Monel 450	Ni 31.0 Fe 0.7 Cu Rem.	Annealed	20	165	385	46
			200	120	300	55
			400	100	290	42
			600	75	150	40
			800	28	58	19
Monel* K-500	Cu 29 Al 2.8 Ti 0.5	Fully heat treated	20	340	680	45
			200	290	650	40
			400	260	600	30
			600	290	460	5
			800	—	185	30

* Registered trade mark.

Table 22.28 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, SHORT-TIME HIGH-TEMPERATURE TENSILE PROPERTIES—*continued*

Alloy	*Nominal composition* %	*Condition*	*Test temperature* °C	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %
Inconel* 600	Cr 16	Hot rolled	20	250	590	50
	Fe 6		400	185	560	50
			600	150	530	10
			800	95	250	20
			1000	—	110	50
Inconel 601	Ni 60.5	Annealed	20	440	760	43
	Cr 23.0		200	410	750	38
	Al 1.4		400	380	740	38
	Fe 15.1		600	325	575	32
			800	170	205	92
			870	100	160	122
Inconel 617	Ni 55.7	Solution	20	330	720	63
	Cr 21.5	Annealed	200	260	640	70
	Co 12.5		400	230	600	72
	Mo 9.0		600	220	580	58
	Al 1.2		800	230	410	65
	C 0.1		1000	80	160	92
Inconel 718	Ni 52.5	Precipitation	20	1180	1350	17
	Cr 19.0	hardened	200	1100	1280	16
	Fe 18.8		400	1080	1240	13
	Nb 5.2		600	960	1160	16
	Mo 3.1		800	720	760	8
	Ti 0.9					
	Al 0.5					
Inconel X-750	Cr 15	Fully heat	20	620	1110	24
	Fe 7	treated	400	590	1100	28
	Ti 2.5		650	280	830	9
	Al 0.6		800	310	370	22
	Nb 0.8		800	100	170	90
Inconel MA 754	Ni 78.0	Annealed	20	560	940	20
	Cr 20.0		200	560	910	18
	Fe 1.0		400	540	860	16
	Y203 0.6		600	500	640	18
			800	230	280	30
			1000	120	160	16
INCO 330	Ni 35.5	Annealed	20	280	580	48
	Fe 44.8		200	220	520	45
	Cr 18.5		400	200	500	44
	Si 1.2		600	165	430	49
			800	120	170	68
			980	70	80	74
INCO 020	Ni 35.0	Annealed	30	300	620	40
	Fe 38.4		200	280	575	40
	Cr 20.0		400	250	560	39
	Cu 3.5		600	185	505	41
	Mo 2.5		800	150	275	59
	Nb 0.6		870	140	220	72
INCO G-3	Ni 49.0	Solution	20	320	690	50
	Cr 22.5	Annealed	200	235	590	62
	Fe 19.5		400	190	555	68
	Mo 7.0		600	175	500	73
	Cu 2.0		800	170	355	66
			1000	75	140	76

* Registered trade mark.

Table 22.28 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, SHORT-TIME HIGH-TEMPERATURE TENSILE PROPERTIES—*continued*

Alloy	*Nominal composition* %	*Condition*	*Test temperature* °C	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %
INCO C-276	Ni 59.0 Mo 16.0 Cr 15.5 Fe 5.5 W 4.0	Annealed	20 200 400 540	415 285 240 220	790 690 660 610	50 56 64 60
INCO-HX	Ni 48.3 Cr 22.0 Fe 18.5 Mo 9.0 Co 1.5 W 0.6 C 0.1	Solution Annealed	20 200 400 600 800 1 000	340 300 225 220 180 40	790 745 700 600 370 110	45 40 48 46 48 56
Incoloy* 800	Fe 45 Cr 21 Ti 0.4 Al 0.4	Annealed	20 600	300 210	600 440	45 40
Incoloy DS	Fe 40 Cr 18 Si 2	Annealed	20 600 800 1 000	300 — — —	700 460 150 75	45 50 90 100
Hastelloy* B-2	Mo 28	Solution treated	200 320 430	451 426 418	885 864 866	50 49 51
Hastelloy C-4	Mo 16 Cr 16	Solution-treated	200 320 430	403 371 320	706 675 656	49 52 64
Hastelloy X	Mo 9 Cr 21 Fe 18	Solution treated	20 600 800 1 000	360 280 230 110	790 620 410 160	45 40 37 45
Nimonic* 75	Cr 20 Ti 0.4	Annealed	20 400 600 800 1 000	420 400 310 110 50	800 740 590 220 90	35 30 30 80 58
Nimonic* 80A	Cr 20 Ti 2.0 Al 1.5	Fully heat treated	20 400 600 800 1 000	740 680 620 490 70	1 240 1 150 1 080 620 120	24 26 20 24 120
Nimonic 90	Cr 20 Co 17 Ti 2.4 Al 1.4	Fully heat treated	20 600 800 1 000	750 680 530 48	1 175 1 030 900 76	30 26 18 130
Nimonic 105	Cr 15 Co 20 Mo 5 Al 5 Ti 1.2	Fully heat treated	20 600 800 1 000	780 720 680 150	1 140 1 040 810 175	22 25 25 42

* Registered trade mark.

Table 22.28 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, SHORT-TIME HIGH-TEMPERATURE TENSILE PROPERTIES— *continued*

Alloy	*Nominal composition* %	*Condition*	*Test temperature* °C	0.2% *Proof stress* MPa	*UTS* MPa	*Elongation* %
Nimonic 115	Cr 14 Co 13 Mo 3 Al 5 Ti 4	Fully heat treated	20 600 800 1 000	860 790 760 200	1 230 1 100 1 020 420	27 20 19 26
				0.1% PS		
Nimonic 263	Cr 20 Co 20 Mo 6 Ti 2 Al 0.5	Fully heat treated	20 600 800 1 000	570 460 390 60	970 790 560 110	40 41 20 65
Nimonic PE 16	Cr 16 Fe 32 Mo 3 Ti 1.0 Al 1.0	Fully heat treated	20 600 800 1 000	490 450 290 46	880 730 390 92	37 27 53 100
Astroloy	Ni 54.8 Cr 15.0 Co 17.0 Mo 5.3 Al 4.0 Ti 3.5	Precipitation hardened	20 540 650 760 870	1 050 965 965 910 690	1 410 1 240 1 310 1 160 770	16 16 18 21 25
Rene 41	Ni 55.4 Cr 19.0 Co 11.0 Mo 11.0 Al 1.5 Ti 3.1	Precipitation hardened	21 540 650 760 870	1 060 1 010 1 000 940 550	1 420 1 400 1 340 1 100 620	14 14 14 11 19
Rene 95	Ni 61.5 Cr 14.0 Co 8.0 Mo 3.5 Nb 3.5 Al 3.5 Ti 2.5	Precipitation hardened	21 540 650 760	1 310 1 250 1 220 1 100	1 620 1 540 1 460 1 170	15 12 14 15
Udimet 500	Ni 53.7 Cr 18.0 Co 18.5 Mo 4.0 Al 2.9 Ti 2.9	Precipitation hardened	21 540 650 760 870	840 765 760 730 495	1 310 1 240 1 210 1 040 640	32 28 28 39 20
Udimet 700	Ni 55.5 Cr 15.0 Co 17.0 Mo 5.0 Al 4.0 Ti 3.5	Precipitation hardened	21 540 650 760 870	965 895 855 825 635	1 410 1 280 1 240 1 030 690	17 16 16 20 27
Waspaloy	Ni 58.7 Cr 19.5 Co 13.5 Mo 4.3 Al 1.3 Ti 3.0	Precipitation hardened	21 540 650 760 870	795 725 690 675 515	1 280 1 170 1 120 795 525	25 23 34 28 35

* Registered trade mark.

Table 22.29 WROUGHT NICKEL AND HIGH NICKEL ALLOYS. CRYOGENIC PROPERTIES

alloy	*Nominal composition* %	*Condition*	*Test temp.* °C	*0.2% Proof stress* MPa	*UTS* MPa	*Elongation* %	*Charpy impact* J	*Notched fatigue strength** MPa
Nickel	Ni 99.0	Annealed	20	160	500	48	230	—
			−75	170	560	58	230	120
			−200	230	710	54	230	140
Monel** 400	Cu 30 Fe 1.5 Mn 1.0	Annealed	20	220	540	52	260	—
			−180	340	800	50	240	—
Monel** K-500	Cu 29 Al 2.8 Ti 0.5	Fully heat treated	20	670	1060	22	74	
			−80	740	1140	24	68	300
			−200	830	1260	30	—	330
			−255	940	1380	28	—	330
Inconel** 600	Cr 16 Fe 6	Annealed	20	230	650	37	240	280
			−80	290	730	40	210	280
			−190	—	—	—	190	300
Inconel 718	Cr 19 Nb 5 Mo 3 Ti 0.9 Al 0.5	Fully heat treated	20	1400	1500	—	—	—
			−80	1400	1600	—	—	—
			−190	1600	1800	—		
Inconel X-750	Cr 15 Fe 7 Ti 2.5 Al 0.6 Nb 0.8	Fully heat treated	20	700	1200	24	—	—
			−75	790	1290	23	—	410
			−200	810	1440	19	—	440
			−255	900	1450	16	—	460
Ni-Span** C-902	Fe 47 Cr 5.5 Ti 2.5 Al 0.5	Fully heat treated	20	760	1210	30	24	320
			−130	860	1410	28	23	310
			−255	1000	1690	25	23	390

* 10^8 cycles Kt = 3.1. ** Registered trade mark.

Table 22.30 WROUGHT NICKEL AND HIGH NICKEL ALLOYS. FATIGUE PROPERTIES

Alloy	*Nominal composition* %	*Condition*	*Test temperature* °C	*Average endurance limit Rotating beam tests* 10^8 *cycles* MPa
Nickel	Ni 99.0	Annealed	20	230
		Cold drawn	20	340
Monel** 400	Cu 30 Fe 1.5 Mn 1.0	Annealed	20	230
		Cold drawn*	20	300
Monel K-500	Cu 29 Al 2.8 Ti 0.5	Annealed	20	260
		Cold drawn and aged	20	320
Inconel** 600	Cr 16 Fe 6	Annealed	20	270
			650	180
			850	75
Inconel 625	Cr 21.5 Mo 9.0 Nb 3.6	Hot rolled	29	460
			427	450
			538	425
			649	390
			760	310

Table 22.30 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, FATIGUE PROPERTIES—*continued*

Alloy	*Nominal composition* %	*Condition*	*Test temperature* °C	*Average endurance limit Rotating beam tests* 10^8 cycles MPa		
Inconel 718	Cr 19 Nb 5 Mo 3 Ti 0.9 Al 0.5	Fully heat treated	20 650	620 500		
Inconel X-750	Cr 15 Fe 7 Ti 2.5 Al 0.6 Nb 0.8	Fully heat treated	20 700	280 340		
Incoloy** 800	Fe 45 Cr 21 Ti 0.4	Annealed	20 500 850	290 260 95		
				0 ± *stress. For lives of*		
				MPa	h	cycles
Nimonic** 75	Cr 20 Ti 0.4	Annealed	20 750	260 190	65 300	10×10^6 10×10^6
Nimonic 90	Cr 20 Co 17 Ti 2.4 Al 1.4	Fully heat treated	750 870 	260 240 140 110	300 1 000 300 1 000	36×10^6 120×10^6 36×10^6 120×10^6
Nimonic 105	Cr 15 Co 20 Mo 5 Al 5 Ti 1.2	Fully heat treated	20 750 870 980	350 250 260 250 240 190 170 124	50 500 50 500 50 500 50 500	3×10^7 3×10^8 3×10^7 3×10^8 3×10^7 3×10^8 3×10^7 3×10^8

* Stress equalized 3 h at 260°C. ** Registered trade marks.

Table 22.31 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, CREEP PROPERTIES—*continued*

Alloy	*Nominal composition* %	*Condition*	*Test temp.* °C	*Stress* MPa *for creep extension of*								
				0.1%			0.2%			1%	*Rupture*	
				300 h	1 000 h	10 000 h	300 h	1 000 h	10 000 h	10 000 h	1 000 h	10 000 h
Nickel	Ni 99.0	Cold drawn	400	—	—	77	—	—	—	220	—	—
Monel* 400	Cu 30 Fe 1.5 Mn 1.0	Hot rolled	400	—	—	140	—	—	—	215	—	—
Monel K-500	Cu 29 Al 2.8 Ti 0.5	Cold drawn and aged	400	—	—	355	—	—	—	—	—	—
Inconel* 600	Cr 16 Fe 6	Hot rolled	400 600	—	—	340 38	—	—	—	— 77	—	—
Inconel 601	Ni 60.5 Cr 23.0 Al 1.4 Fe 15.1	Annealed	650 760 870 980 1095	195 63 30 14 7	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —

Table 22.31 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, CREEP PROPERTIES

Alloy	Nominal composition %	Condition	Test temp. °C	Stress MPa for creep extension of 0.1% 300 h	0.1% 1 000 h	0.1% 10 000 h	0.2% 300 h	0.2% 1 000 h	0.2% 10 000 h	1% 10 000 h	Rupture 1 000 h	Rupture 10 000 h
Inconel 617	Ni 55.7 Cr 21.5 Co 12.5 Mo 9.0 Al 1.2 C 0.1	Solution Annealed	650 760 870 980 1095	320 150 58 25 10	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —
Inconel 718	Ni 52.5 Cr 19.0 Fe 18.8 Nb 5.2 Mo 3.1 Ti 0.9 Al 0.5	Precipitation hardened	595 650 705 760	760 590 370 170	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —
Incoloy* 800H	Fe 45 Cr 21 Tl 0.4 Al 0.4	Solution treated	650 870 980	— — —	115 24 7	90 20 3.8	— — —	— — —	— — —	— — —	— — —	121 24 8.3
Inconel X-750	Cr 15 Fe 7 Ti 2.5 Al 0.6 Nb 0.8	Fully heat treated	595 650 730 815 870	— — — — —	— — — — —	— — — — —	— — — — —	— 420 — 110 —	— — — — —	— — — — —	630 470 260 110 50	— — — — —
Inconel MA 754	Ni 78.0 Cr 20.0 Fe 1.0 Y203 0.6	Annealed	650 760 870 980 1095 1150	256 199 158 129 94 78	— — — — — —	— — — — — —	— — — — — —	— — — — — —	— — — — — —	— — — — — —	— — — — — —	— — — — — —
INCO 330	Ni 35.5 Fe 44.8 Cr 18.5 Si 1.2	Annealed	760 870 980 1095	48 21 8.6 5.4	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —	— — — —
INCO-HX	Ni 48.3 Cr 22.0 Fe 18.5 Mo 9.0 Co 1.5 W 0.6 C 0.1	Solution Annealed	760 815 870 925 980	110 72 45 26 15	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —	— — — — —
Nimonic* 75	Cr 20 Ti 0.4	Annealed	650 750 815 870 925 980	56 25 — — — —	— — — — — —	— — — — — —	— — — — — —	62 29 — — — —	51 25 — — — —	— — — — — —	170 50 24 15 10 8	— — — — — —
Nimonic 80A	Cr 20 Ti 2.0 Al 1.5	Fully heat treated	650 705 750 815	390 — 170 93	185 — 120 58	— — 51 23	460 — 200 108	390 — 150 73	260 — 66 26	280 — 90 29	500 350 220 110	280 — 85 34
Nimonic 90	Cr 20 Co 17 Ti 2.4 Al 1.4	Fully heat treated	650 705 750 815 870	400 — 185 85 49	348 — 137 57 29	250 — 65 28 15	450 — 220 108 60	400 — 175 77 37	310 — 85 31 17	325 — 110 38 18	455 360 240 150 75	340 — 135 54 28

Table 22.31 WROUGHT NICKEL AND HIGH NICKEL ALLOYS, CREEP PROPERTIES—*continued*

				Stress MPa *for creep extension of*								
				0.1%			0.2%			1%	*Rupture*	
Alloy	*Nominal composition* %	*Condition*	*Test temp.* °C	300 h	1 000 h	10 000 h	300 h	1 000 h	10 000 h	10 000 h	1 000 h	10 000 h
Nimonic 105	Cr 15 Co 20 Mo 5 Al 5 Ti 1.2	Fully heat treated	750	285	230	--	325	280	193	—	363	208
			815	162	119	—	193	148	93	102	224	120
			870	86	57	—	108	83	34	45	134	57
			940	31	22	—	48	31	12	22	62	35
			980	—	—	—	—	—	—	—	32	--
Nimonic 115	Cr 14 Co 13 Mo 3 Al 5 Ti 4	Fully heat treated	750	355	310	—	385	340	—	—	450	250
			815	—	—	—	—	—	—	—	310	—
			850	154	116	51	222	137	53	74	—	108
			870	—	—	—	—	—	—	—	210	—
			950	51	34	14	63	43	15	17	—	52
			925	—	—	—	—	—	—	—	130	—
			980	—	—	—	—	—	—	—	80	—
			1000	22	15	—	29	19	6	8	—	--
Astroloy	Ni 54.8 Cr 15.0 Co 17.0 Mo 5.3 Al 4.0 Ti 3.5	Precipitation hardened	650	770	—	—	—	—	—	—	—	—
			760	425	—	—	—	—	—	—	—	—
			870	170	—	--	—	—	—	—	—	—
			980	55	—	—	--	--	—	—	--	-
Rene 41	Ni 55.4 Cr 19.0 Co 11.0 Mo 11.0 Al 1.5 Ti 3.1	Precipitation hardened	650	705	—	—	—	—	—	—	—	—
			760	345	—	—	—	—	—	—	-	—
			870	115	—	—	—	—	—	—	--	—
Rene 95	Ni 61.5 Cr 14.0 Co 8.0 Mo 3.5 Nb 3.5 Al 3.5 Ti 2.5	Precipitation hardened	650	860	—	—	—	—	—			
Udimet 500	Ni 53.7 Cr 18.0 Co 18.5 Mo 4.0 Al 2.9 Ti 2.9	Precipitation hardened	650	760	—	—	--	—	—	—	—	--
			760	325	--	----	—	—	—	—	—	--
			870	125	—	—	—	—	—	—	--	—
Udimet 700	Ni 55.5 Cr 15.0 Co 17.0 Mo 5.0 Al 4.0 Ti 3.5	Precipitation hardened	650	705	—	—	—	—	—	—	—	- -
			760	425	—	—	—	—	—	—	—	- -
			870	200	--	—	—	—	—	—	—	--
			980	55	—	—	--	--	—	—	—	—
Waspaloy	Ni 58.7 Cr 19.5 Co 13.5 Mo 4.3 Al 1.3 Ti 3.0	Precipitation hardened	650	615	--	---	—	—	—	—	—	-
			760	290	—	—	—	—	—	—	—	—
			870	110	—	—	—	—	—	—	—	—

*Registered trade mark.

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22.6 Mechanical properties of titanium and titanium alloys

Table 22.32 TITANIUM AND TITANIUM ALLOYS. CORRESPONDING GRADES OR SPECIFICATIONS

IMI designation	*UK British Standards (Aerospace series) and Min. of Def.* DTD series*	*France* AIR-9182, 9183, 9184	*Germany BWB series*†	*AECMA recommendations*	*USA AMS series*‡	*USA ASTM series*
IMI 115	BS TA 1, DTD 5013	T-35	3.7024	Ti-P01		ASTM grade 1
IMI 125	BS TA 2,3,4,5	T-40	3.7034	Ti-P02	AMS 4902, 4941, 4942, 4951	ASTM grade 2
IMI 130	DTD 5023, 5273, 5283, 5293	T-50			AMS 4900	ASTM grade 3
IMI 155	BS TA 6	T-60	3.7064	Ti-P04	AMS 4901	ASTM grade 4
IMI 160	BS TA 7,8,9				AMS 4921	
IMI 230	BS TA 21, 22, 23, 24, BS TA 52–55, 58	T-U2.	3.7124	Ti-P11		
IMI 315	DTD 5043					
IMI 317	BS TA 14, 15, 16, 17	T-A5E		Ti-P65	AMS 4909, 4910, 4926, 4924, 4953, 4966	
IMI 318	BS TA 10, 11, 12, 13, 28, 56	T-A6V	3.7164	Ti-P63	AMS 4911, 4928, 4934, 4935, 4954, 4965, 4967	ASTM grade 5
IMI 318 ELI (extra low interstitial)	–	T-A6VELI			AMS 4907, 4930, 4931	ASTM grade 3, F. 136.
IMI 325	–	T-A3V2.5	3.7194		AMS 4943 4944	ASTM grade 9
IMI 550	BS TA 45–51, 57	T-A4DE	3.7184	Ti-P68		
IMI 551	BS TA 39–42					
IMI 624	–	T-A6Zr4 DE	3.7144		AMS 4919, 4975, 4976	
IMI 646	–	–	–	–	AMS 4981	
IMI 662	–	–	3.7174	–	AMS 4918, 4971, 4978, 4979	
IMI 679	BS TA 18–20, 25-27				AMS 4974	
IMI 680	DTD 5213	T-E11DA				
IMI 685	BS TA 43, 44	T-A6ZD	3.7154	Ti-P67		
IMI 811	–	T-A8DV			AMS 4915, 4916	
IMI 834	–	T-A6E Zr4Nb				

*UK BS 3531 Part I (Metal Implants in Bone Surgery), and Draft British Standard for Lining of Vessels and Equipment for Chemical Processes, Part 9, also refer.

†Germany DIN 17850, 17860, 17862, 17863, 17864 (3.7025/35/55/65), and TUV 230-1-68 Group I, II, III and IV also refer.

‡USA MIL-T-9011, 9046, 9047, 14577, 46038, 46077, 05-10737 and ASTM B265-69, B338-65, B348-59T, B367-61T. B381-61T, B382-61T also refer.

Table 22.33 PURE TITANIUM, TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

*Designation**	*Grade*	*Condition*	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation %* *on* 50 mm	*on* 5D	*Red. in area* %	*Specification bend radius* 180° bend <1.83 mm	<3.25 mm	*Mod. of elasticity* GPa	*Mod. of rigidity* GPa
Iodide	Pure, 60 HV		103	241	55		80				
IMI 115	Commercially pure	Annealed sheet	255	370	33			1t	2t		
		Annealed rod	220	370		40	70				
		Annealed wire		390	38						
IMI 125	Commercially pure	†Annealed sheet	340	460	30			$1\frac{1}{2}$t	2t		
		Annealed rod	305	460		28	57				
		Annealed tube	325	480	35						
IMI 130	Commercially pure	Annealed sheet	420	540	25			2t+	$2\frac{1}{2}$t		
		Annealed rod	360	540		24	48			105	38
		Annealed wire		550	24						
		Hard-drawn wire		700	11.5						
IMI 155	Commercially pure	Annealed sheet	540	640	24			$2\frac{1}{2}$t	3t		
IMI 160	Commercially pure	Annealed rod	500	670		23	46				
		Annealed wire		690	24						

*IMI Nomenclature. †Up to 16.3 mm.

Table 22.34 TITANIUM ALLOYS TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE

*Designation**	*Nominal composition* %	*Condition*	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation %* *on* 50 *mm*	*on* 5D	*Red. in area* %	*Specification bend radius* 180°	*Mod. of elasticity* GPa	*Mod. of rigidity* GPa
IMI 230	Cu 6.0	Annealed sheet	520	620	24			2t(0.5–3 mm)	125	
		Aged sheet	670	770	20			2t(typical)		
		Annealed rod	500	630		27	45			
		Aged rod	580	740		22	41		125	
IMI 260	Pd 0.2	Similar to commercially Pure Titanium 115								
IMI 261	Pd 0.2	Similar to commercially Pure Titanium 125								
IMI 315	Al 2.0 Mn 2.0	Annealed rod	590	720		21	50		120	
IMI 317	Al 5.0 Sn 2.5	Annealed sheet	820	860	16			4t(<2 mm) $4\frac{1}{2}$t(≤3 mm)		
		Annealed rod	930	1000		15	37		120	

continued overleaf

Table 22.34 TITANIUM ALLOYS TYPICAL MECHANICAL PROPERTIES AT ROOM TEMPERATURE (*continued*)

*Designation**	*Nominal composition* %	*Condition*	*0.2% proof stress* MPa	*Tensile strength* MPa	*Elongation %* on 50 mm	on 5D	*Red. in area* %	*Specification bend radius* 180°	*Mod. of elasticity* GPa	*Mod. of rigidity* GPa
IMI 318	Al 6.0 V 4.0	Annealed sheet	1110	1160	10			5t(≤3.25 mm)		
		Annealed rod	990	1050		15	40		106	46
		Aged rod (fastener stock)	1050	1140		15	40			
		Hard-drawn wire		1410	4					
IMI 550	Al 4.0 Mo 4.0 Sn 2.0 Si 0.5	F.h.t. rod	1070	1200		14	42		116	
IMI 551	Al 4.0 Mo 4.0 Sn 4.0 Si 0.5	F.h.t.rod	1140	1300		12	40		113	43
IMI 679	Sn 11.0 Al 2.25 Mo 1.0 Si 0.2	Quenched and aged rod	1080	1230		11	40		108	46
		Air-cooled and aged rod	1000	1120		13	45			
IMI 680	Sn 11.0 Mo 4.0 Al 2.25 Si 0.2	Quenched and aged rod	1200	1350		12	37		115	
		Furnace-cooled and aged rod	1080	1160		14	47			
IMI 685	Al 6.0 Zr 5.0 Mo 0.5 Si 0.25	F.h.t. rod	920	1020		11	22		124	47
IMI 829	Al 5.5 Sn 3.5 Zr 3.0 Nb 1.0 Mo 0.3 Si 0.3	F.h.t. rod	848	965		12	22		120	
IMI 834	Al 5.8 Sn 4.0 Zr 3.5 Nb 0.7 Mo 0.5 Si 0.35 C 0.06	F.h.t. rod	931	1067		13	22		120	

*IMI Nomenclature.

Table 22.35 COMMERCIALLY PURE TITANIUM SHEET, TYPICAL VARIATION OF PROPERTIES WITH TEMPERATURE

*Designation**	*Temperature* °C	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation on* 50 mm %	*Mod. of elasticity* GPa	*Transformation temperature* °C
IMI 115	−196	442	641	34		$\alpha/\alpha+\beta$
	−100	306	444	34		865
	20	207	337	40		
	100	168	296	43		
	200	99	218	38		
	300	53	167	47		
	400	42	131	52		
	450	36	120	49		
IMI 125	20	334	479	31		
	100	250	397	32		
	200	184	300	40		
	300	142	232	45		
	400	127	190	38		
	450	119	175	35		
IMI 130	−196	730	855	28		
	−100	590	737	28		
	20	394	547	28	108	
	100	315	462	29	99	$\alpha+\beta/\beta$
	200	205	331	37	91	915
	300	139	247	40	83	
	400	102	199	34	65	
	450	93	182	28		
	500				46	
IMI 155	20	460	625	25		
	100	372	537	26		
	200	219	386	32		
	300	151	281	36		
	400	110	221	33		
	450	96	202	26		

*IMI nomenclature.

Table 22.36 TITANIUM ALLOYS, TYPICAL VARIATION OF PROPERTIES WITH TEMPERATURE

Designation	*Nominal composition* %	*Condition*	*Temperature* °C	*0.2% Proof stress* MPa	*Tensile strength* MPa	*Elongation %* on 50 mm	*Elongation %* on 5D	*Red in area* %	*Mod. of elasticity* GPa	*Transformation temperature* °C
IMI 230	Cu 2.5	S.h.t (trans.)	20	500	605	24				$\alpha/\alpha+\beta$
			100	410	540	29				790
			200	310	450	33				
			300	270	410	31				$\alpha+\beta/\beta$
			400	250	380	30				895 ± 10
			500	220	380	33				
		Aged sheet (trans.)	20	622	761	24				
			100	553	704	23				
			200	471	635	26				
			300	457	607	23				
			400	429	573	19				
			500	357	468	21				
		Aged	20	638	795		22	40	107	
			100	601	761		21	39	100	
			200	507	687		23	45	92	
			300	496	658		20	50	85	
			400	415	592		21	53	78	
			500	361	491		27	57	71	
IMI 260	Pd 0.2	Similar to IMI 115								
IMI 262	Pd 0.2	Similar to IMI 125								
IMI 315	Al 2.0 Mn 2.0	Annealed rod	20	618	757		18	41	110	$\alpha+\beta/\beta$
			100	510	649		21	46	107	915 ± 20
			200	386	525		22	48	97	
			300	293	432		19	50	86	
			400	278	417		18	56	76	
			500	201	340		22	72	62	
IMI 317	Al 5.0 Sn 2.5	Annealed rod	20	822	919		18	39	112	$\alpha/\alpha+\beta$
			100	692	798		19	40	109	950
			200	494	638		18	44	105	
			300	415	576		19	42	89	$\alpha+\beta/\beta$
			400	374	522		18	41	84	1025 ± 20
			500	346	485		21	57	81	

IMI 318	Al 6.0 V 4.0	Annealed rod	−196	1560	1675	6	29		$\alpha + \beta/\beta$ 1000 ± 15	
			−100	1165	1265	12	33			
			20	970	1040	15	38	106		
			100	825	920	17	43	102		
			200	710	815	18	49	96		
			300	645	750	18	56	90		
			400	580	700	18	63	85		
			500	450	605	26	72	79		
			600	125	265	58	85			
			700	40	135	127	94			
		Heat-treated rod (fastener stock)	20	1035	1145	14				
			100	925	1035	15				
			200	805	925	16				
			300	710	850	16				
			400	635	805	18				
			500	540	695	25				
IMI 550	Al 4.0 Mo 4.0 Sn 2.0 Si 0.5	F.h.t. rod	20	1081	1220	15	49	116	$\alpha + \beta/\beta$ 980 ± 10	
			100	965	1130	15	49	112		
			200	805	960	16	60	106		
			300	700	900	16	55	101		
			400	655	835	17	60	95		
			500	585	780	19	68	90		
			600	310	585	26	83	85		
IMI 551	Al 4.0 Mo 4.0 Sn 4.0 Si 0.5	F.h.t rod	20	1250	1390	10	27	113	$\alpha + \beta/\beta$ 1050 ± 15	
			100	1125	1300	11	29	108		
			200	925	1145	14	38	103		
			300	815	1045	15	38	98		
			400	745	970	14	41	93		
			500	670	920	18	55	88		
			600	460	755	27	65	81		
IMI 679	Sn 11.0 Zr 5.0 Al 2.25 Mo 1.0 Si 0.2	Quenched and aged rod	20	1050	1230	10	37		$\alpha + \beta/\beta$ 950 ± 10	
			100	940	1145	11	43			
			200	820	1020	12	45			
			300	740	990	11	46			
			400	710	940	11	46			
			450	680	910	11	46			
		Air-cooled and aged rod	20	1020	1095	14	41	108		
			100	895	995	16	47	103		
			200	770	900	16	49	99		
			300	695	865	14	49	94		
			400	665	850	14	48	90		
			500	600	795	15	48	85		

continued overleaf

Table 22.36 TITANIUM ALLOYS, TYPICAL VARIATION OF PROPERTIES WITH TEMPERATURE (*continued*)

Designation	*Nominal composition* %	*Condition*	*Temperature* °C	*0.2% Proof stress* MPa	*Tensile strength* MPa	*Elongation %* *on* 50 mm	*Elongation %* *on* 5D	*Red in area* %	*Mod. of elasticity* *GPa*	*Transformation temperature* °C
IMI 680	Sn 11.0 Mo 4.0 Al 2.25 si 0.2	Quenched and aged rod	20 100 200 300 400 450	1180 1020 905 835 805 725	1330 1190 1105 1075 1020 975		12 14 15 15 14 13	43 49 53 56 57 54	106 100 96 94 90 88	$\alpha + \beta/\beta$ 945 ± 15
		Furnace-cooled and aged rod	−196 −100 20	1630 1280 1030	1730 1380 1130		$8\frac{1}{2}$ 10 15	36 43 49		
IMI 685	Al 6.0 Zr 5.0 Mn 0.5 Si 0.25	F.h.t. rod	−196 −100 20 100 200 300 400 500	1480 1140 890 800 720 650 595 535	1560 1270 1030 935 850 800 750 695		6 10 12 13 15 16 18 19	13 18 22 22 24 27 31 37	124 120 114 108 102 95	$\alpha + \beta/\beta$ 1020 ± 10
IMI 829	Al 5.5 Sm 3.5 Zr 3.0 Nb 1.0 Mo 0.3 Si 0.3	F.h.t. rod	20 200 500 540 600	895 622 501 487 457	1028 792 665 653 634		$10\frac{1}{2}$ $14\frac{1}{2}$ 15 16 14	22 28 36 42 38	119 110 93 91 88	$\alpha + \beta\beta$ 1015 ± 15
IMI 834	Al 5.8 Sn 4.0 Zr 3.5 Nb 0.7 Mo 0.5 Si 0.35 C 0.06	F.h.t. rod	20 100 200 300 400 500 600	931 840 746 700 662 609 505	1067 962 885 832 790 764 656		13 13 14 14 14 15 16	22 23 27 32 36 42 50	120 116 112 106 102 96 92	1045

Table 22.37 COMMERCIALLY PURE TITANIUM – TYPICAL CREEP PROPERTIES

IMI designation	*Temperature* °C	*Stress* MPa *to produce* 0.1% *plastic strain in*		
		1000 h	10 000 h	100 000 h
IMI 130	20	288	270	207
	50	243	221	165
	100	179	165	119
	150	140	133	96
	200	113	116	77
	250	96	101	66
	300	87	83	55
IMI 155	20	309	278	260
	50	252	232	213
	100	188	170	157
	150	145	131	122
	200	116	108	104
	250	102	97	94
	300	93	90	86

Table 22.38 TITANIUM ALLOYS – TYPICAL CREEP PROPERTIES

IMI designation	*Nominal composition* %	*Condition*	*Temperature* °C	*Stress* MPa *to produce* 0.1% *total plastic strain in*			
				100 h	300 h	500 h	1000 h
IMI 230	Cu 2.5	Aged sheet	200	435	–	–	–
			300	375	–	–	–
			400	220	–	–	–
			450	109	–	–	–
		Annealed sheet	20	360	–	–	–
			100	279	–	–	–
			200	235	–	–	–
			300	202	–	–	–
			400	125	–	–	–
IMI 317	Al 5.0	Annealed rod	20	633	608	–	593
	Sn 2.5		100	474	463	–	458
			200	370	–	–	370
			300	359	–	–	359
			400	337	–	–	337
			500	162	119	–	88
IMI 318	Al 60	Annealed rod	20	832	818	–	788
	V 4.0		100	704	680	–	676
			200	638	636	–	635
			300	576	568	–	–
			400	287	144	–	102
			500	32	18	–	–
IMI 550	Al 4.0	Fully heat-	300	724	718	–	710
	Mo 4.0	treated bar	400	551	516	–	471
	Sn 2.0		450	254	174	–	101
	Si 0.5		500	82	51	–	31
IMI 551	Al 4.0	Fully heat-	400	621	575	540	501
	Mo 4.0	treated rod	450	307	217	–	–
	Sn 4.0						
IMI 679	Sn 11.0	Air-cooled and	20	896	880	–	880
	Zr 5.0	aged rod	150	703	695	–	672
	Al 2.25		300	664	664	–	649
	Mo 1.0		400	579	571	–	526
	Si 0.2		450	448	386	–	247
			500	131	93	–	62

continued overleaf

Table 22.38 TITANIUM ALLOYS – TYPICAL CREEP PROPERTIES (*continued*)

IMI designation	*Nominal composition %*	*Condition*	*Temperature* °C	*Stress* MPa *to produce* 0.1% *total plastic strain in* 100 h	300 h	500 h	1000 h
IMI 680	Sn 11.0 Mo 4.0 Al 2.25 Si 0.2	Quenched and aged rod	20	1127	1112	–	–
			150	945	942	–	–
			200	862	856	–	–
			300	804	788	–	–
			400	555	540	–	–
			450	298	209	–	–
			500	88	51	–	–
		Furnace-cooled and aged rod	300	570	–	–	–
			350	540	–	–	–
			400	490	–	–	–
IMI 685	Al 6.0 Zr 5.0 Mo 0.5 Si 0.25	Heat-treated forgings	200	599	–	592	589
			300	551	–	541	535
			400	497	–	480	462
			450	461	–	431	426
			500	408	–	340	–
IMI 829	Al 5.5 Sn 3.5 Zr 3.0 Nb 1.0 Mo 0.3 Si 0.3	Fully heat treated rod	450	478	–	–	–
			500	420	–	–	–
			550	300	–	–	–
			600	130	–	–	–
IMI 834	Al 5.8 Sn 4.0 Zr 3.5 Nb 0.7 Mo 0.5 Si 0.35 C 0.06	Heat-treated forgings	500	461	–	–	–
			550	339	–	–	–
			600	205	–	–	–

Table 22.39 TITANIUM AND TITANIUM ALLOYS – TYPICAL FATIGUE PROPERTIES

IMI designation	*Nominal composition %*	*Condition*	*Temperature* °C	*Tensile strength* MPa	*Details of test*	*Endurance limit for* 10^7 cycles *stated)* MPa
					Rotating bend	
IMI 115	Commercial purity	Annealed rod	Room	354	Smooth $K_t = 1$	± 193
				354	Notched $K_t = 3$	± 123
					Rotating bend	
IMI 125	Commercial purity	Annealed rod	Room	417	Smooth $K_t = 1$	± 232
				417	Notched $K_t = 3$	± 154
					Rotating bend	
IMI 130	Commercial purity	Annealed rod	Room	550	Smooth $K_t = 1$	± 270
				550	Notched $K_t = 2$	± 170
				550	Notched $K_t = 3.3$	± 170
					Direct stress (Zero mean)	
				550	Smooth $K_t = 1$	± 263
				550	Notched $K_t = 1{,}5$	± 247
				550	Notched $K_t = 2$	± 170
				550	Notched $K_t = 3.3$	± 116
				589	Smooth $K_t = 1$	± 278
				589	Notched $K_t = 2$	± 147
				589	Notched $K_t = 3$	± 123
				589	Notched $K_t = 4$	± 116

Table 22.39 TITANIUM AND TITANIUM ALLOYS – TYPICAL FATIGUE PROPERTIES (*continued*)

IMI designation	*Nominal composition %*	*Condition*	*Temperature °C*	*Tensile strength MPa*	*Details of test*	*Endurance limit for 10^7 cycles stated) MPa*
					Direct stress (Zero mean)	
IMI 160	Commercial purity	Annealed rod	Room	674	Smooth K_t	± 376
IMI 230	Cu 2.5	Annealed sheet	Room	564	Reversed bend	± 390
		Aged sheet	room	772	Reversed bend	± 490
					Direct stress (Zero minimum)	
		Aged sheet	room	761	Smooth K_t = 1	0→560
					Rotating bend	
		Annealed rod	room	598	Smooth K_t = 1	± 370
			400		Smooth K_t = 1	± 150
					Direct stress (Zero mean)	
		Annealed	Room	638	Smooth K_t = 1	± 280
					Rotating bend	
		Aged rod	Room	700	Smooth K_t = 1	± 450
			400	–	Smooth K_t = 1	± 290
					Direct stress (Zero mean)	
		Aged rod	Room	792	Smooth K_t = 1	± 470
					Notched K_t = 3.3	± 200
IMI 260	Pd 0.2	Similar to IMI 115				
IMI 262	Pd 0.2	Similar to IMI 125				
					Rotating bend	Limits for this alloy 10^8 cycles
IMI 317	Al 5.0 Sn 2.5	Annealed rod	Room	–	Smooth K_t = 1.0	± 371
					Notched K_t = 2.0	± 263
					Notched K_t = 3.3	± 239
					Direct stress (Zero mean)	
					Smooth K_t = 1.0	± 433
					Notched K_t = 1.5	± 278
					Notched K_t = 2.0	± 201
					Notched K_t = 3.3	± 154
					Rotating bend	
IMI 318	Al 6.0 V 4.0	Annealed rod	Room	960	Smooth K_t = 1	± 470
				960	Notched K_t = 2.7	± 230
					Direct stress (Zero minimum)	
				1015	Smooth K_t = 1	0→750
				1015	Notched K_t = 1	0→325
					Direct stress (Zero minimum)	

continued overleaf

Table 22.39 TITANIUM AND TITANIUM ALLOYS – TYPICAL FATIGUE PROPERTIES (*continued*)

IMI designation	*Nominal composition %*		*Condition*	*Temperature °C*	*Tensile strength MPa*	*Details of test*	*Endurance limit for 10^7 cycles stated) MPa*
IMI 550	Al	4.0	Fully heat-treated rod	Room	1180	Smooth $K_t = 1$	0→850
	Mo	4.0			1180	Notched $K_t = 3$	0→350
	Sn	2.0					
	Si	0.5					
						Rotating bend	
						Rotating bend	
						Smooth $K_t = 1$	± 587
						Notched $K_t = 2.4$	± 394
						Rotating bend	
IMI 551	Al	4.0	Fully heat-treated rod	Room	–	Smooth $K_t = 1$	± 750
	Mo	4.0			–	Notched $K_t = 3.2$	± 430
	Sn	4.0					
	Si	0.5					
						Rotating bend	
IMI 679	Sn	11.0	Air-cooled and aged rod	Room	–	Smooth $K_t = 1.0$	±641*
	Zr	5.0		200	–	Smooth $K_t = 1.0$	±510*
	Al	2.25		400	–	Smooth $K_t = 1.0$	±510*
	Mo	1.0		450	–	Smooth $K_t = 1.0$	± 556
	Si	0.2		500	–	Smooth $K_t = 1.0$	± 495
						Rotating bend	(Limits for 2×10^7 cycles
IMI 680	Sn	11.0	Quenched and aged rod	Room	1272	Smooth $K_t = 1$	± 710
	Mo	4.0			1272	Notched $K_t = 2$	± 340
	Al	2.25			1272	Notched $K_t = 3.3$	± 293
	Si	0.2					
						Direct stress (Zero mean	(Limits for 2×10^7 cycles
				Room	1272	Smooth $K_t = 1$	± 695
						Notched $K_t = 2$	± 371
						Notched $K_t = 3.3$	± 232
						Rotating bend	(Limits for 10^8 cycles)
				Room	–	Smooth $K_t = 1$	± 648
				200	–	Smooth $K_t = 1$	± 495
				400	–	Smooth $K_t = 1$	± 479
						Direct stress Zero	
			Furnace-cooled rod	Room	1100	Smooth $K_t = 1$	± 680
						Direct stress (Zero mean)	
IMI 685	Al	6.0	Fully heat-treated rod	20	–	Smooth $K_t = 1$	± 440
	Zr	5.0		450	–	Smooth $K_t = 1$	± 300
	Mo	0.5		520	–	Smooth $K_t = 1$	± 260
	Si	0.25					
						Direct stress (Zero minimum)	
				450	–	Smooth $K_t = 1$	0→475
				520	–	Smooth $K_t = 1$	0→425
						Direct stress (Zero minimum)	
			Fully heat-treated forging	Room	–	Smooth $K_t = 1$	0→640
				Room	–	Notched $K_t = 3.5$	0→220
				475	–	Smooth $K_t = 1$	0→460
				475	–	Notched $K_t = 3.5$	0→210

Table 22.39 TITANIUM AND TITANIUM ALLOYS – TYPICAL FATIGUE PROPERTIES (*continued*)

IMI designation	*Nominal composition %*		*Condition*	*Temperature °C*	*Tensile strength MPa*	*Details of test*	*Endurance limit for 10^7 cycles stated) MPa*
IMI 829	Al	5.5	Fully heat-treated rod	Room	–	Direct stress (Zero minimum) Smooth $K_t = 1$ Notched $K_t = 3$	 0→550 0→260
	Sn	3.5					
	Zr	3.0					
	Nb	1.0					
	Mo	0.3					
	Si	0.3					
IMI 834	Al	5.8	Fully heat-treated rod	Room	–	Direct stress (Zero minimum) Smooth $K_t = 1$	 0→577
	Sn	4.0			–	Notched $K_t = 2$	0→363
	Zr	3.5					
	Nb	0.7					
	Mo	0.5					
	Si	0.35					
	C	0.06					

*Limits for 10^8 cycles.

Table 22.40 IZOD IMPACT PROPERTIES OF TITANIUM AND TITANIUM ALLOYS

IMI designation	*Nominal composition %*		*Condition*	*Izod value Joules (ft lbf)**							
				−196 °C	*−78 °C*	*20 °C*	*100 °C*	*200 °C*	*300 °C*	*400 °C*	*500 °C*
IMI 130†	Commercially pure		Annealed rod	–	62.4 (46)	61.0 (45)	62.4 (46)	72 (53)	82 (60½)	84 (62)	82 (60½)
IMI 317	Sn	5.0	Annealed rod	17.6 (13)	20.3 (15)	27.1 (20)	35.2 (26)	52.8 (39)	63.7 (47)	70.5 (52)	71.8 (53)
	Al	2.5									
IMI 318	Al	6.0	Annealed rod	13.5 (10)	14.9 (11)	20.3 (15)	25.7 (19)	40.6 (30)	65.0 (48)	83.5 (63)	92.0 (68)
	V	4.0									
IMI 550	Al	4.0	Fully heat-treated rod	–	–	19.0 (14)	–	–	–	–	–
	Mo	4.0									
	Sn	2.0									
	Si	0.5									

IMI designation	*Nominal composition %*		*Condition*	*Charpy value Joules (ft lbf)*							
				−196 °C	*−78 °C*	*20 °C*	*100 °C*	*200 °C*	*300 °C*	*400 °C*	*500 °C*
IMI 551	Al	4.0	Fully heat-treated rod	13.5 (10)	19 (14)	20.3 (15)	21.7 (16)	24.4 (18)	26.5 (19½)	28.5 (21)	31.2 (23)
	Mo	4.0									
	Sn	4.0									
	Si	0.5									
IMI 679	Sn	11.0	Air-cooled and aged	10.8 (8)	13.5 (10)	14.9 (11)	16.3 (12)	19 (14½)	25 (18½)	30 (22)	33.9 (25)
	Zr	5.0									
	Al	2.25									
	Mo	1.0									
	Si	0.2									
IMI 680	Sn	11.0	Quenched and aged rod	8.1 (6)	8.8 (6½)	10.8 (8)	12.2 (9)	14.9 (11)	17.6 (13)	20.3 (15)	25.7 (19)
	Mo	4.0									
	Al	2.25									
	Si	0.2									
IMI 685	Al	6.0	Fully heat-treated rod	31.2 (23)	39.3 (29)	43.4 (32)	–	–	–	–	–
	Zr	5.0									
	Mo	0.5									
	Si	0.25									

*BSS 131 (1) 0.45 in diameter straight notched test pieces. †Izod values of commercial purity titanium are appreciably affected by variation in hydrogen content within commercial limits (0.008% maximum) in Ti 130 rod.

22.7 Mechanical properties of zinc and zinc alloys

Table 22.41 MECHANICAL PROPERTIES OF ZINC ALLOYS AT ROOM TEMPERATURE

	Composition						*Properties*		
Zinc	Unalloyed zinc is generally used only in the wrought form. The data here are some typical values								
	Zn min	Pb	Cd max	Sn	Fe	*Total* Pb + Cd + Sn + Fe + Cu (max)		*Parallel to rolling direction*	*Across rolling direction*
BS 3436 Zn 1	99.99	0.003	0.003	0.001	—	0.01	Zn 1		
Zn 2	99.95	0.03	0.02	0.001	0.01	0.05	Tensile strength		
Zn 3	99.5	0.35	0.15	0.001	0.03	0.5	MPa	120	150
Zn 4	98.5	1.35	0.15	0.02	0.04	1.5	Elongation %	60–80	40–60
							Hardness Vickers	30	
Zinc-copper-titanium	Cu	Ti				*Balance*			
	0.14	0.1–0.15				zinc of 99.995% purity	Tensile strength MPa	180	216
							Elongation %	35	20
							Hardness (Brinell)	40–45	

These alloys are used principally in pressure die castings and other castings. Properties are given in Table 26.36 page 26–61 Casting and foundry data

22.8 Mechanical properties of zirconium and zirconium alloys

Table 22.42 MECHANICAL PROPERTIES OF ZIRCONIUM ALLOYS AT ROOM TEMPERATURE

Material	*Nominal composition*	*Condition*	0.1% *proof stress* MPa	*UTS* MPa	*Elongation* %	*Macro-hardness* HV	*Reference*
Zr (ex iodide)	>99.9% purity Impurities in ppm by wt $O_2$65, $N_2$15, $H_2$12, Hf 35, Ni 20	Crystal bar, cold rolled and vacuum annealed 2 h at 750°C	100–130	170–210	40–45 on 1 in gauge	85–100	1
Zr (ex sponge)	>99.6% purity Impurities in ppm by wt $O_2$1300, $N_2$80, $H_2$20, Hf 400, Ni 40	Sheet material, cold rolled and vacuum annealed 2 h at 750°C	250–310 in r.d.	350–390 in r.d.	23–31 on 1 in gauge	195–215	1
Zircaloy 2	Sn 1.2–1.7% Fe 0.07–0.2% Cr 0.05–0.15% Ni 0.03–0.08% Zr–remainder	Plate materials cold rolled and annealed 1 h at 750°C	340† in r.d. 490 in t.d.	450 in r.d. 520 in t.d.	29 in r.d. 23 in t.d. on 1 in gauge	205–220*	2 1
Zirconium 30*	Cu 0.46–0.66% Mo 0.50–0.60% Zr–remainder	Sheet and strip	220–320 in r.d.	470–550 in r.d.	20–31 on 2 in gauge	130–180	3
Zr/2½% Nb	Nb 2.55% Impurities in ppm by wt $O_2$1050, $N_2$20, $H_2$10, Hf 70 N < 40	Plate, hot rolled at 750°C later annealed ½ h at 700°C	470 for forged product	590 for forged product 410–500 ppm O_2 600–2 500 ppm O_2	24 gauge un-specified‡	150–500 ppm O_2 230–2 500 ppm O_2	4 3

Table 22.42 MECHANICAL PROPERTIES OF ZIRCONIUM ALLOYS AT ROOM TEMPERATURE—*continued*

Material	*Nominal composition*	*Condition*	0.1% *proof stress* MPa	*UTS* MPa	*Elongation* %	*Bend radius* (min.)	*Reference*
Zr 702	Commercially pure with up to Hf 4.5	Annealed sheet	207	379	16	5T	
Zr 704	Cr + Fe 0.2–0.4 Sn 1–2	Annealed sheet	241	413	14	5T	
Zr 705	Nb 2.5 O_2 0.18	Annealed sheet	379	552	16	3T	
Zr 706	Nb 2.5 O_2 0.16	Annealed sheet	345	510	20	$2\frac{1}{2}$T	

* Imperial Metal Industries Nomenclature.

Table 22.43 MECHANICAL PROPERTIES OF ZIRCONIUM ALLOYS AT ELEVATED TEMPERATURE

Material	*Nominal composition*	*Test temperature* °C	0.1% *proof stress* MPa	*UTS* MPa	*Elongation* %	*Reference*
Zr (ex sponge)	>99.6% purity Impurities in ppm by wt O_2 1 300, N_2 80, H_2 20, Hf 400, Ni 40	371	50†	110	57	3
Zircalloy 2	Sn 1.2–1.7% Fe 0.07–0.2% Cr 0.05–0.15% Ni 0.03–0.08% Zr–remainder	300	92–126	210–260	33–44 on 2 in gauge	3
Zirconium 30	Cu 0.46–0.66% Mo 0.50–0.60% Zr–remainder	300	160	250	34 on $5.65\sqrt{A}$ gauge	3
Zr/$2\frac{1}{2}$% Nb	Nb 2.55% Impurities in ppm by wt O_2 1 050, N_2 20, H_2 10, Hf 70, Ni < 40	300	210	340 280–500 ppm O_2* 350–2 500 ppm O_2*	33 gauge unspecified	3 4*
Zr 702	Commercially pure with up to Hf 4.5	100 200 300 400	296 262 207 145	413 351 275 227	32 37 47 54	
Zr 704	Cr + Fe 0.2–0.4	100 200 300 400	344 289 241 193	510 489 434 358	22 23 27 32	
Zr 705	Nb 2.5 O_2 0.18	100 200 300 400	455 379 317 269	565 489 427 372	26 31 33 33	

r.d. rolling direction.
t.d. transverse direction.
* Imperial Metal Industries nomenclature.
† 0.2% proof stress.

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22.9 Tin and its alloys

The applications of tin are governed very largely by its low melting point, excellent fluidity when molten, relative softness, formability and readiness to form alloys with other metals.

The low melting point of tin means that at normal ambient temperature the metal is nearly 60% of its melting point on the absolute Temperature Scale. This results in rather low mechanical strength at room temperature, as would be expected from any metal tested at a temperature corresponding to such a high proportion of its Absolute melting point, i.e. 505 K. Because of this, pure tin recrystallizes readily at room temperature. Consequently, unlike the majority of industrial metals, only slight work hardening occurs initially in tin, followed by work-softening with further deformation due to grain growth. A similar behaviour is found in tin-rich alloys. The mechanical properties recorded for tin-rich alloys are strongly dependent on impurity levels and the rate of strain.

Within reasonable limits any tin-base alloy can be die cast successfully. The choice of alloy, therefore, rests on such matters as mechanical properties, wear resistance or cost rather than on any consideration of the casting behaviour.

PURE TIN—MECHANICAL PROPERTIES

Tensile strength (at 0.4 mm/mm min) at	20°C	14.5 MPa
	100°C	11.0 $N mm^{-2}$
	200°C	4.5 $N mm^{-2}$
Shear strength at 20°C		12.3 MPa
Hardness at	20°C	3.9 HB
	100°C	2.3 HB
	200°C	0.9 HB
Young's modulus at 20°C		49.9 GPa
Rigidity modulus at 20°C		18.4 GPa
Poisson's ratio		0.357
Creep strength at 15°C		
(approx. life at 2.3 $N mm^{-2}$)		170 days
(approx. life at 1.4 $N mm^{-2}$)		550 days
Fatigue strength for 10^8 reversals at 15°C		±2.5 MPa
Elastic modulus (tension)		
As cast		41.6 GPa
Self annealed		44.3 GPa
Impact strength		
0°C		44.1 J
150°C		22.7 J

Note: Mechanical properties are very dependent on the rate of loading.

Table 22.44 TIN-RICH SOLDERS—PHYSICAL PROPERTIES (BULK)

Properties	*Nominal composition* (wt%)					
	63Sn37Pb	60Sn40Pb	50Sn50Pb	95Sn5Sb	96.5Sn3.5Ag	62Sn36Pb2Ag
Liquidus (°C)	183	188	216	240	221	189
Solidus (°C)	183	183	183	234	221	177
Density ($g cm^{-3}$)	8.42	8.52	8.89	7.25	7.29	8.5
Volume change on freezing (%)	na	−2.4	−2.3	na	na	na
Coefficient of thermal expansion	$24.7 \times 10^{-6} K^{-1}$	$23.9 \times 10^{-6} K^{-1}$	$23.4 \times 10^{-6} K^{-1}$	na	na	$27 \times 10^{-6} K^{-1}$
Specific heat ($J kg^{-1} K^{-1}$)	na	150	210	na	na	na
Thermal conductivity ($W m^{-1} K^{-1}$)	50	50	46.5	na	na	na
Electrical conductivity (% IACS)	11.9	11.5	10.9	11.9	14	na
Electrical resistivity ($\mu\Omega$ cm)	14.5	14.9	15.8	14.5	12.31	na
Viscosity (poise)	0.0133 (at 280°C)	0.01682 (at 350°C)	0.0142 (at 280°C)	na	na	na
Surface tension ($mN m^{-1}$)	490 (at 280°C)	481 (at 260°C)	476 (at 280°C)	na	na	na

Note na = not available.

Table 22.45 TIN-RICH SOLDERS—MECHANICAL PROPERTIES (BULK)
Specifications: B.S. 219, ASTM B32, DIN 1707.

Properties	*Nominal composition* (wt%)					
	63Sn37Pb	60Sn40Pb	50Sn50Pb	95Sn5Sb	96.5Sn3.5Ag	62Sn36Pb2Ag
Tensile strength ($N mm^{-2}$) (Tested at 0.05 mm (min))						
at 20°C	na	19	na	31	37	43
at 100°C	na	4	na	20	na	19
Elongation (%)						
at 20°C	na	135	na	25	31	7
at 100°C	na	>100	na	21	na	na
Hardness (HB)	17	16	14	15	15	na
Young's modulus (GPa)	na	29.99	na	49.99	na	22.96
Creep strength (MPa) for life of 1000 h						
at 20°C	na	29	na	21	22	na
at 100°C	na	4.5	na	9	na	27
Impact strength (J)	20	20	21	27	na	na

Note: Tensile strength, hardness etc., are very dependent on the rate of loading and temperature of testing.
na = not available.

Table 22.46 PROPERTIES OF SOME TIN-RICH ALLOYS
Mechanical properties

Alloy	*Nominal composition* (Wt%) Sn	Sb	Cu	Pb	Bi	*UTS* (MPa)	*Elongation* (%)	*Compressive yield Strength* (MPa) 0.125% set 20°C	100°C	0.25% set 20°C	100°C	*Hardness* (HB)	*Liquidus* (°C)	*Solidus* (°C)	*Density* ($g\,cm^{-3}$)
Whitemetal bearing alloys BS 332: 1987	Rem	4.5	4.5	—	—	64 Chillcast 62 Die cast	9 Chillcast 2 Die cast	30.3	17.9	88.2	47.6	17 Chillcast	371	223	7.34
ASTM B23 DIN 1703	Rem	7.5	3.5	—	—	77 Chillcast	18 Chillcast	42	21	103	60	24 Chillcast	354	241	7.39
	Rem	8	8	—	—	69 Die cast	1 Die cast	46	21	117	6.8	27 Chillcast 30 Die cast	422	240	7.45
	Rem	12	3	10	—	27 Chillcast	na	38.3	14.8	111.4	47.6	27 Chillcast	306	184	7.53
Die casting alloys ASTM B102	Rem	15	2	18	—	22.5 Chillcast	na	34	14	103	46	22.5 Chillcast	296	181	7.75
Many bearing alloys can be used for die casting	Rem	13	5	—	—	69 Die cast	1	na	na	na	na	29 Die cast	na	na	na
Pewter BS 5140 ASTM B560 DIN 17810	Rem	6	2	—	—	64.7 Chillcast 59 Annealed for 1 h air cooled 52 Cold rolled, 32% reduction	24 Chillcast 40 Annealed for 1 h air cooled 52 Cold rolled, 32% reduction	na	na	na	na	23.8 Chillcast 9.5 Annealed for 1 h air cooled 8 Cold rolled, 32% reduction	295	244	7.28
Fusible alloy Cerrocast Ostalloy 338 Indalloy 100	Rem	—	—	—	40	55	200 Slow loading	na	na	na	na	22	170	138	8.2

Note: Tensile strength, hardness, etc, are very dependent on the rate of loading and casting conditions.
Properties are typical values.
na = not available.

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22.10 Steels

The tables are a guide only; for full information the relevant specifications must be consulted.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES

		Composition %						Limiting ruling section		Properties (minima unless otherwise stated)					
Material	*British or other standard*	C	Mn	Ni	Cr	*Other elements*	*Condition**	mm	in	*UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_o}$) %	*Impact* J	*Hardness* HB	*Remarks*
1. *Carbon steels with up to 1.7%* Mn *content, including free cutting steels* ((BS 970:Part 1:1983)															
0.10 C	BS 055M15 (En2)	0.2 max	0.8 max	—	—	0.05 max	AR	150	6	310	—	25	—	121	
0.20 C	BS 070M20	0.16	0.50	—	—	P, S	N	152	6	430	215	21	—	126/179	General
		0.24	0.90	—	—	0.050 max		254	10	400	200	20	—	—	constructional
							CD	13	½	530	385	12	—	—	steel suitable for
								76	3	430	340	14	—	—	welding.
							HT	19	¾	540/690	355	20	41‡	—	
0.26	BS 070M26	0.22	0.50	—	—	P, S	N	64	2½	490	245	20	—	—	Medium strength
		0.30	0.90	—	—	0.050 max		254	10	430	215	20	—	—	engineering steel
							CD	13	½	570	430	11	—	—	
								76	3	490	370	13	—	—	
							HT	13	½	620/770	415	16	34‡	—	
								29	1⅛	540/690	355	20	41‡	—	
0.30 C	BS 080M30 (En5)	0.26	0.60	—	—	P, S	N	150	6	490	245	20	—	143/192	General
		0.34	1.00	—	—	0.050 max		250	10	460	230	19	—	126/179	engineering steels
							CD	13	½	600	450	10	—	—	widely used in the
								76	3	530	385	12		—	bright drawn
							HT	19	¾	625/775	415	16	34‡	179/229	condition
								64	2½	550/700	340	18	34	152/207	
0.38 C	BS 080M36	0.32	0.60	—	—	P, S	N	64	2½	540	280	16	27‡	—	
		0.40	1.00	—	—	0.050 max		254	10	490	245	18	—	—	
							CD	13	½	620	480	9	—	—	
								76	3	540	400	11		—	
							HT	13	½	789/850	465	16	34‡	201/255	
								29	1⅛	625/775	400	16	34‡	179/229	

0.40 C Steel	BS 080M40	0.36	0.60	—	—	P, S	N	150	6	550	280	16	20‡	152/207	Nuts and bolts,
	(En8)	0.44	1.00	—	—	0.050 max		250	10	510	245	17	—	146/197	forgings and
							CD	13	$\frac{1}{2}$	660	530	7	—	—	general
								76	3	570	430	10	—	—	engineering
							HT	19	$\frac{3}{4}$	690/850	465	16	34‡	201/255	parts
								64	$2\frac{1}{2}$	620/770	385	16	34‡	179/229	
0.46 C Steel	BS 080M46	0.42	0.60	—	—	P, S	N	64	$2\frac{1}{2}$	620	310	14	—	—	Nuts and bolts,
		0.50	1.00	—	—	0.050 max		254	10	540	280	15	—	—	forgings and
							CD	13	$\frac{1}{2}$	690	555	7	—	—	general
								76	3	620	480	9	—	—	engineering
							HT	13	$\frac{1}{2}$	770/930	525	14	—	—	parts
								102	4	620/770	370	16	—	—	
0.50 C Steel	BS 080M50	0.45	0.60	—	—	P, S	N	152	6	620	310	14	—	—	Gears and
	(En43A)	0.55	1.00	—	—	0.050 max		254	10	570	280	14	—	—	machined parts
							CD	13	$\frac{1}{2}$	730	585	8	—	—	for flame or
								76	3	650	510	10	—	—	induction
							HT	13	$\frac{1}{2}$	850/1 000	570	12	—	—	hardening
								63	$2\frac{1}{2}$	690/850	430	14	—	—	
0.55 C Steel	BS 070M55	0.50	0.50	—	—	P, S	N	64	$2\frac{1}{2}$	700	355	12	—	—	General machine
		0.60	0.90	—	—	0.050 max		254	10	600	310	13	—	—	parts requiring
							CD	13	$\frac{1}{2}$	790	620	7	—	—	higher wear
								76	3	710	570	9	—	—	resistance
							HT	19	$\frac{3}{4}$	850/1 000	570	12	—	—	
								102	4	690/850	415	14	—	—	
0.19 C	BS 120M19	0.15	1.00	—	—	P, S	N	102	4	490	295	20	34‡	—	Armature shafts.
1.2 Mn		0.23	1.40	—	—	0.050 max		254	10	460	260	19	—	—	High tensile
Steel							CD	13	$\frac{1}{2}$	600	450	11	—	—	bolts. Lifting
								76	3	530	385	12	34‡	—	gear chains.
							HT	19	$\frac{3}{4}$	690/850	510	16	34‡	—	Automotive
								102	4	540/690	355	18	47‡	—	forgings
0.19 C	BS 150M19	0.15	1.30	—	—	P, S	N	150	6	550	325	18	41‡	152/207	Armature shafts.
1.5 Mn	(En14A)	0.23	1.70	—	—	0.050 max		250	10	510	295	17	—	146/197	High tensile
Steel							HT	29	$1\frac{1}{8}$	690/850	510	16	41‡	—	bolts. Lifting
								152	6	540/690	340	18	54‡	—	gear chains. Automotive forgings

‡ Grain controlled steel.
* AR—As rolled. N—Normalized. CD—Cold drawn. HT—Hardened and tempered.

Table 22.47 FORGED OR ROLLED STEELS -ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

		Composition %						Limiting ruling section		Properties (minima unless otherwise stated)					
Material	*British or other standard*	C	Mn	Ni	Cr	*Other elements*	*Condition*[a]	mm	in	*UTS* MPa	*Yield stress* MPa	*Elong.* (g) $5.65\sqrt{S_o}$ %	*Impact* J	*Hardness* HB	*Remarks*
0.28 C–1.2 Mn Steel	BS 120M28	0.24 0.32	1.00 1.40	— —	— —	P, S 0.050 max	N	152 254	6 10	540 530	325 310	16 17	34‡ —	— —	Not recommended for new designs
							CD	13 76	½ 3	650 570	510 430	8 10	— —	— —	
							HT	29 102	1⅛ 4	690/850 620/770	510 415	16 16	34‡ 41‡	— —	
0.28 C–1.5 Mn Steel	BS 150M28 (En14B)	0.24 0.32	1.30 1.70	— —	— —	P, S 0.050 max	N	152 254	6 10	590 560	355 325	16 16	34‡ —	— —	Not recommended for new designs
							HT	13 152	½ 6	770/930 620/770	570 400	16 16	34‡ 47‡	— —	
0.36 C–1.2 Mn Steel	Bs 120M36 (En15B)	0.32 0.40	1.00 1.40	— —	— —	P, S 0.050 mm	N	150 250	6 10	590 570	355 340	15 16	— —	174/223 163/217	General engineering steel
							CD	13 76	½ 3	690 620	555 480	7 9	— —	— —	
							HT	19 102	¾ 4	770/930 620/770	570 415	14 18	34‡ 41‡	— —	
0.36 C–1.5 Mn Steel	BS 150M36 (En15)	0.32 0.40	1.30 1.70	— —	— —	P, S 0.050 max	N	150 250	6 10	620 600	385 355	14 15	— —	179/229 170/223	
							HT	13 150	½ 6	850/1 000 620/770	635 400	12 18	34‡ 47‡	248/302 179/229	
Low C Free cutting steel	BS 220M07 (En1A)	0.15 max	0.90 1.30	— —	— —	S 0.20 0.30	CD	13 76	½ 3	460 370	380 240	7 10	— —	— —	Free cutting mild steels to be machined in high speed automatic lathes
							HR	102	4	360	215	22	—	103 min	
Low C Free cutting steel	BS 230M07	0.15 max	0.90 1.30	— —	— —	S 0.25 0.35	CD	13 76	½ 3	460 370	350 225	7 10	— —	— —	Free cutting mild steels to be machined in high speed automatic lathes
							HR	102	4	360	215	22	—	103 min	

Low C Free cutting steels containing lead	DIN 9SMnPb28	0.14 max	0.90 1.30	— —	— —	S 0.24 0.32 Pb 0.15 0.30	CD	16 64 102	$\frac{5}{8}$ $2\frac{1}{2}$ 4	510/690 415/665 385/635	415 310 245	7 9 10	— — —	— — —	Free cutting mild steels to be machined in high speed automatic lathes	
0.28 C Free cutting steel	BS 216M28	0.24 0.32	1.10 1.50	— —	— —	S 0.12— 0.20	CD	13 76	$\frac{1}{2}$ 3	570 490	430 370	10 12	— —	— —	Not recommended for new designs	
							HT	19 64	$\frac{3}{4}$ $2\frac{1}{2}$	620/770 540/690	430 355	18 20	34‡ 34‡	— —		
0.36 C Free cutting steel	BS 212M36 (En8M)	0.32	1.00	—	—	S 0.12— 0.20	CD	13 76	$\frac{1}{2}$ 3	620 540	480 400	7 9	— —	— —	Free cutting medium strength engineering steels for machine parts and engine components, etc.	
							HT	13 100	$\frac{1}{2}$ 4	700/850 550/700	495 340	16 20	54‡ 34‡	201/255 152/207		
0.36 C Free cutting higher Mn	BS 216M36 (En15AM)	0.32 0.40	1.30 1.70	— —	— —	S 0.12– 0.20 P 0.060 Si 0.25 max	CW	16 76	$\frac{5}{8}$ 3	650 570	510 420	7 9	— —	— —	Free cutting medium strength engineering steels for machine parts and engine	
							HT	102 29	4 $1\frac{1}{8}$	550/700 700	340 480	20 16	34‡ 34‡	152/207 201/255		
0.36 C Free cutting	BS 212M36 (En8M)	0.40 0.48	1.00 1.40	— —	— —	S 0.12— 0.20 P 0.060 Si 0.25 max	HT	100 13	4 $\frac{1}{2}$	550/700 770/850	340 495	20 16	28 28	152/207 201/255	Free cutting medium strength engineering steels	
2. *Low alloy high strength weldable steels* (BS 4360:1986, 1501:Pt 2:1988, 1503:1980, ASTM Standards)																
Mn steel	BS 4360–40B	0.20 max	1.50 max	—	—	P, S 0.05 max	AR	16	$\frac{5}{8}$	340/500	235	25	27	—	Structural steel	
Mn steel	BS 4360–40C	0.18 max	1.50 max	—	—	P, S 0.04 max	AR	16	$\frac{5}{8}$	340/500	235	25	27	—	Structural steel	
Mn steel	BS 4360–40D	0.16 max	1.50 max	—	—	P+S 0.04 max	N	16	$\frac{5}{8}$	340/500	235	25	27 at −20°C	—	Structural steel	
								40	$1\frac{1}{2}$	340/500	225	25	27 at −20°C	—		

‡ Grain controlled steel.
* N—Normalized. CD—Cold drawn. HT—Hardened and tempered. HR—Hot rolled. CW—Cold worked. AR—As rolled.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
Mn steel	BS 4360–43A	0.25 max	1.60 max	—	—	P+S 0.05 max	AR	16	$\frac{5}{8}$	430/580	275	22	—	—	Structural steel
Mn steel	BS 4360–43B	0.2 max	1.50 max	—	—	P+S 0.05 max	AR	16	$\frac{5}{8}$	430/580	275	22	27 at 20°C	—	Structural steel
Mn steel	BS 4360–43C	0.10 max	1.50 max	—	—	P+S 0.04 max	AR	16	$\frac{5}{8}$	430/580	275	22	27 at 0°C	—	Structural steel
Mn Nb (V) steel	BS 4360–43D†	0.16 max	1.50 max	—	—	Nb+V 0.10 max	N	16	$\frac{5}{8}$	430/580	275	22	27 at −20°C	—	Structural steel
						P+S 0.04 max		40	$1\frac{1}{2}$	430/580	265	22	27		
Mn steel	BS 4360–43EE	0.16 max	1.50 max	—	—	P 0.04 S 0.03	N	16	$\frac{5}{8}$	430/580	275	22	27 at −50°C	—	Structural steel
								40	$1\frac{1}{2}$	430/580	265	22	—	—	
								63	$2\frac{1}{2}$	430/580	255	22	—	—	
Mn Nb (V) steel	BS 4360–50B†	0.2 max	1.50 max	—	P+S 0.05 max	Nb+V 0.10 max	AR	16	$\frac{5}{8}$	490/640	355	20	—	—	Structural steel. Plate, bars, sections, tubes
		0.20 max	1.50 max	—	—	"	N	100	4	490/640	325	20	—	—	
Mn Nb (V) steel	BS 4360–50C†	0.20 max	1.50 max	—	—	"	AR	16	$\frac{5}{8}$	490/640	355	20	27 at 0°C	—	Structural steel. Plate bars, sections, tubes
		0.20 max	1.50 max	—	—	"	N	100	4	490/640	325	20		—	
Mn Nb (V) steel	BS 4360–50D†	0.18 max	1.50 max	—	—	Nb+V 0.10 max	N	16	$\frac{5}{8}$	490/640	355	20	27 at −30°C	—	Structural steel. Plate, bars, sections, tubes
						P+S 0.04 max	N	63	$2\frac{1}{2}$	490/640	340	20		—	
Mn Nb (V) steel	BS 4360-50EE†	0.18 max	1.50 max	—	—	Nb+V 0.15 max	N	16	$\frac{5}{8}$	490/640	355	20	27 at −50°C	—	Structural steel
								40	$1\frac{1}{2}$	"	345	20			
								63	$2\frac{1}{2}$	"	340	20	27	—	

Mn Nb (V) Steel	BS 4360–55C†	0.22 max	1.60 max	—	P+S 0.04 max	"	AR	16	$\frac{5}{8}$	550/700	450	19	27 at 0°C	—	Structural steel. Plate bars, sections, tubes
Mn Nb (V) Steel	BS 4360–55E†	0.22 max	1.60 max	—	"	"	N N	16 63	$\frac{5}{8}$ $2\frac{1}{2}$	550/700 550/700	450 400	19 19	27 at −50°C	—	Structural steel. Plate, bars, sections, tubes
Cr–Cu Steel	Bs 4360 WR 50A	0.12 max	0.30/ 0.50 max	0.65 max	0.50 1.25	Cu 0.2 0.55 P 0.070 0.150 S 0.050	AR	12 38	$\frac{1}{2}$ $1\frac{1}{2}$	480 480	345 325	21 21	27 at 0°C —	— —	Weather resisting plate
Cr–CuV Steel	BS 4360 WR 50B	0.19 max	0.90 1.25	0.01 0.06	0.50 0.65	Cu 0.25 0.40 V 0.02 0.10	AR	12 50	$\frac{1}{2}$ 2	480 480	345 345	21 21	27 at 0°C	— —	Weather resisting plate
Cr–Cu–V Steel	BS 4360 WR 50C	0.22 max	0.90 145	0.01 0.06	0.50 0.65	Cu 0.25 0.40 V 0.02 0.10	AR or N	12 50	$\frac{1}{2}$ 2	480 480	345 340	21 21	27 at −15°C	—	
Mn V Steel	ASTM A 242	0.22 max	1.25 max	—	—	V 0.02 min	AR	38	$1\frac{1}{2}$	420	310	21	—	—	Structural quality
Mn V Nb Steel	ASTM A 572	0.22 max	1.35 max	—	—	Nb 0.01 min and/or V 0.02 min N 0.015 max	AR	19	$\frac{3}{4}$	550	450	17	—	—	Structural quality
Mo B Steel	BS 1501–261 (Fortiweld)	0.10 0.17	0.40 0.80	0.30 max	0.25 —	Mo 0.40–0.60 B 0.001 0.005	N	89	$3\frac{1}{2}$	550/670	420	16 (transv)	20	—	Pressure vessel plate
1CrMo Steel	BS 1501–620	0.09 0.18	0.40 0.65	0.30 max	0.80 1.15	Mo 0.45–0.60 Al 0.02 Cu 0.30	NT	150	6	430/550	255	16	—	—	Pressure vessel plate

*AR—As rolled. N—Normalized. HT—Hardened and tempered. NT—Normalized and tempered.

†It is permissible for these steels to be supplied with no Nb or V. If no grain refining elements, or if grain refining elements other than Al, Nb or V are used, the manufacturer shall inform the purchaser at the time or order. If Nb and V are used the total shall be less than 0.10%.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
1CrMo Steel	BS 1501–622 –690	0.12 0.18	0.40 0.80	0.30 max	2.00 2.50	Mo 0.90 1.10 Al 0.02 Cu 0.30	NT	50	2	690/820	555	15	—	—	Pressure vessel plate
1CrMo Steel	BS 1503–620 –440	0.18	0.40 0.70	0.40 max	0.85 1.15	Mo 0.45 0.65 Al 0.020 Cu 0.30	NT, HT	—	—	440/590	275	19	—	—	Pressure vessel forgings
1¼CrMo Steel	Bs 1501–621	0.09 0.17	0.40 9.65	0.30 max	1.00 1.50	Mo 0.45– 0.60	NT	150 76	6 3	490/650 480/600	310 340	16 18	—		Pressure vessel steel
1¼CrMo Steel	Bs 1503–621 –460	0.18	0.40 0.70	0.40 max	1.10 1.40	Mo 0.45 0.65 Al 0.020 Cu 0.30	QT	—	—	460/610	275	18	41	—	Pressure vessel forgings
1¼CrMoV Steel	ASTM A 517 Grade E (SSS100)	0.12 0.20	0.40 0.70	— —	1.40 2.00	Cu 0.30 0.40 Mo 0.40– 0.60 V 0.04 or Ti 0.10 + B	HT	64	2½	790/930	700	15	—	—	Pressure vessel plate
MnCrMoV Steel	BS 1503–271 –560	— 0.17	1.00 1.50	0.30 0.70	0.50 1.00	Mo 0.20– 0.35 V 0.05 0.10 Al 0.020 Cu 0.30	NT	—	—	560/710	370	17	41	—	Pressure vessel forgings
MnCrMoV Steel	BS 1502–271	0.17 max	1.00 1.50	0.30 0.70	0.50 1.00	Mo 0.20– 0.35 V 0.05– 0.10 Al 0.02	NT or QT	160	6	560/710	370	19	—	—	Pressure vessel forgings

MnNiMo Steel	ASTM A533 Grade B	0.25 max	1.15 1.50	0.40 0.70	— —	Mo 0.45–0.60	HT	102	4	620/793	482	16	—	—	Pressure vessel plate
CrMoZr Steel	WG Proprietary steel (N-A-XTRA 70)	0.20 max	0.70–1.10	— —	0.60–1.00	Si 0.50–0.90 Mo 0.20–0.60 Zr 0.06–0.12	HT	25	1	790/930	700	16	—	—	
NiCuMo Steel	UK Proprietary steel (Nicuage Type 1)	0.06 max	0.40 0.65	0.70 1.00	— —	Cu 1.00–1.30 Nb 0.02 min	AR	13	½	540/630	500/580	25	Charpy V 61–135 at −10°C 41–115 at −20°C	—	Structural steel resistant to atmospheric corrosion. Good low temperature toughness
							Aged at 500/570°C	13	½	630/740	590/680	20	41–115 at −10°C 34–81 at −20°C	—	
NiCuMo Steel	ASTM A588–87 Grade K	0.17 max	0.50 max	0.40 max	0.40 0.70	Mo 0.10 max Cu 0.30 0.50 Nb 0.005 0.05	AR	102	4	480	34	21	—	—	—
NiCrMoVNb Steel	BS 1501–281	0.08 0.14	1.00 1.50	0.60 1.00	0.40 0.70	Mo 0.24 0.30 V 0.04–0.12	NT	150	6	590/690	430	16 (transv)	Charpy V 68 at −10°C 27 at −40°C	—	Pressure vessel plate
						Al 0.020 Cu 0.04 0.12		25	1	640/760	500	16 (transv)			

*NT—Normalized and tempered. HT—Hardened and tempered. QT—Quenched and tempered. AR—As rolled.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	British or other standard	Composition % C	Mn	Ni	Cr	Other elements	Condition*	Limiting ruling section mm	in	Properties (minima unless otherwise stated) UTS MPa	Yield stress MPa	Elong. (gl $5.65\sqrt{S_0}$) %	Impact J	Hardness HB	Remarks
NiCrMoVB Steel	ASTM A517F (T1)	0.10 0.20	0.60 1.00	0.70 1.00	0.40 0.65	Mo 0.40–0.60 V 0.03–0.08 Cu 0.15–0.50 +B	HT	63	2½	790/930	700	16	Charpy V 20 at −45°C	—	Pressure vessel plate
NiCrMo Steel	UK Proprietary steel	0.22 max	1.00 1.20	0.70 0.85	0.90 1.10	Mo 0.45–0.60	HT	—	—	660 (Typical values)	501 (Typical values)	20	Charpy V 120	—	Pressure vessel forgings
2¼CrMo Steel	BS 1501–622 –515	0.09 0.15	0.30 0.60	0.30 max	2.00 2.50	Mo 0.90–1.0 Al 0.020 Cu 0.30	NT	150	6	500/670	285	16	—	—	Pressure vessel plate
	ASTM A542	0.15 max	0.30 0.60	— —	2.00 2.50	Mo 0.90–1.10	HT	102	4	710/835	590	16	—	—	Plate
	BS 1503–622 (Esshete CRM2)	0.08 0.15	0.40 0.70	0.40 max	2.00 2.50	Mo 0.90–1.10	NT or HT	—	—	540/700	370	19	—	—	Pressure vessel forgings
5CrMo Steel	BS 1503–625 –570	0.15 max	0.30 0.80	0.40 max	4.00 6.00	Mo 0.45–0.65 Al 0.020 Cu 0.30	NT or HT	—	—	520/670	365	18	27	—	Pressure vessel forgings
5CrMo Steel	Bs 1503–625 –590	0.18 —	0.30 0.80	0.40 max	4.00 6.00	Mo 0.45–0.65	NT or HT	—	—	590/740	450	17	41	—	Pressure vessel forgings
3NiCrMo Steel	ASTM A543 (HY 80)	0.18 max	0.40 —	2.25 3.25	1.00 1.50	Mo 0.45–0.60 V 0.03 max	HT	102	4	710/835	590	17	—	—	Plate
	ASTM A543 (HY 100)	0.20 max	0.40 —	2.50 3.50	1.30 1.80	Mo 0.45–0.60 V 0.30 max	HT	102	4	790/930	700	16	—	—	Plate

3.25NiCrMo Steel	ASTM A508 Class 4a	0.23 max	0.20 0.40	2.75 3.90	1.50 2.00	Mo 0.40–0.60 V 0.03 max	HT	—	—	790	700	16	Charpy V 47 at −30°C	—	Pressure vessel forgings	
3½NiCrMo Steel	BS 1501-503	0.15 max	0.80 max	3.25 3.75	0.30 max	Mo 0.10 max	NT or HT	38	1½	450	265	22	Charpy V 34 at −80°C 18 at −100°C	-	Pressure vessel plate	
5NiCrMoV Steel	ASTM (HY 130)	0.12 max	0.60 0.90	4.75 5.25	0.40 0.70	Mo 0.30–0.65 V 0.05–0.10	HT	102	4	990	900	15	Charpy V 88 at −20°C	-	Plate	
3. *Low alloy direct hardening steels including ultra high strength and steels suitable for nitriding* (BS 970:Part 1:1988, 4670:1971, DIN 17200:1969; 17211:1970, Stahl Eisen Werkstoffblatt 550-57)																
1Ni Steel	BS 503M40 (En12)	0.36 0.44	0.70 1.00	0.70 1.00	— —	— —	HT	22 254	¾ 10	770/930 620/770	585 430	15 17	40 27	—	Forgings	
½Cr Steel	DIN 38Cr2	0.34 0.41	0.50 0.80	— —	0.40 0.60	— —	HT	16 102	⅜ 4	790/930 590/740	540 340	14 17	— —	— —		
½Cr Steel	DIN 46Cr2	0.42 0.50	0.50 0.80	— —	0.40 0.60	— —	HT	16 102	⅜ 4	880/1 080 680/835	630 450	12 15	— —	— —		
¾Cr Steel	Bs 526M60 (En11)	0.55 0.65	0.50 0.80	— —	0.50 0.80	— —	HT	64 102	2½ 4	1 000/1 160 850/1 000	740 620	8 11	— —	— —		
1Cr Steel	DIN 34Cr4	0.30 0.37	0.60 0.90	— —	0.90 1.20	— —	HT	16 102	⅜ 4	880/1 080 680/835	680 465	12 15	— —	— —		
1Cr Steel	Bs 530M40 (En18)	0.36 0.44	0.60 0.90	— —	0.90 1.20	— —	HT	29 100	1⅛ 4	850/1 000 700/850	680 525	13 17	50 50	248/302 201/255	Bright bar	
1½MnMo Steel	BS 605M36 (En16)	0.32 0.40	1.30 1.70	— —	— —	Mo 0.22–0.32	HT	150 19	6 ¾	700/850 1 000/1 150	525 850	17 12	50 42	201/255 293/352		
1½MnMo Steel	BS 606M36 (En16M)	0.32 0.40	1.30 1.70	— —	— —	Mo 0.22–0.32 S 0.15–0.25	HT	100 29	4 1⅛	700/850 850/1 000	525 680	15 11	50 35	201/255 248/302	Free cutting steel	

*HT—Hardened and tempered. NT—Normalized and tempered.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

		Composition %						*Limiting ruling section*	*Properties (minima unless otherwise stated)*					
Material	*British or other standard*	C	Mn	Ni	Cr	*Other elements*	*Condition**	mm in	*UTS* MPa	*Yield stress* MPa	*Elong.* (g) $5.65\sqrt{S_0}$ %	*Impact* J	*Hardness* HB	*Remarks*
¾CrMo Steel	UK Proprietary	0.53 (Typical)	0.70	—	0.70	Mo 0.40	HT	508 20	805 (Typical values)	540 (Typical values)	14	—	—	Crankshaft forgings
1CrMo Steel	DIN 25CrMo4	0.22 0.29	0.50 0.80	— —	0.90 1.20	Mo 0.15– 0.30	HT	40 1½ 150 6	790/930 635/790	585 415	14 16	— —	— —	
1CrMo Steel	DIN 34CrMo4	0.30 0.37	0.50 0.80	— —	0.90 1.20	Mo 0.15 - 0.30	HT	100 4 250 10	790/930 680/835	550 465	14 15	— –	– ·	
1CrMo Steel	BS 708M40 (En19A)	0.36 0.44	0.70 1.00	— —	0.90 1.20	Mo 0.15– 0.25	HT	150 6 29 1½	700/850 925/1075	525 755	17 12	50 42	201/255 269/331	
1CrMo Steel	BS 709M40 (En19)	0.36 0.44	0.70 1.00	0.40 max	0.90 1.20	Mo 0.25– 0.35	HT	250 10 29 1½	700/850 1000/1150	495 850	15 12	28 42	201/255 293/352	
1CrMo Steel	Bs 711M40	0.36 0.44	0.60 1.00	0.40 max	0.90 1.50	Mo 0.25– 0.40 max	HT	500 20 250 10	700/850 800/950	500 600	12/16 10/14	14/22 11/18	207/255 235/285	Forgings
3CrMo Steel	BS 722M24 (En40B)	0.20 0.28	0.45 0.70	— —	3.00 3.50	Mo 0.45– 0.65	HT	150 6 254 10	925/1075 850/1000	755 650	12 13	42 35	269/331 245/302	Nitriding steel
3CrMo Steel	DIN 32CrMo12	0.28 0.35	0.40 0.70	0.30 max	2.80 3.30	Mo 0.30 0.50	HT	150 6 250 10	930/1130 880/1080	740 680	11 12	— —	— ·	Nitriding steel
MnNiMo Steel	Bs 785M19	0.15 0.23	1.40 1.80	0.40 0.70	0.40 max	Mo 0.15 0.35	HT	250 10 500 20	600/750 600/750	440 440	14/18 14/18	20/34 24/41	174/223 174/223	Forgings
1½NiCrMo Steel	Bs 817M40 (En24)	0.36 0.44	0.45 0.70	1.30 1.70	1.00 1.40	Mo 0.20 0.35	HT	250 10 29 1½	850/1000 1075/1225	650 940	13 11	35 35	248/302 311/375	Bright bar or nitriding
1½NiCrMo Steel	Bs 818M40	0.36 0.44	0.45 0.85	1.30 1.80	1.00 1.50	Mo 0.20– 0.40	HT	1000 39 250 10	800/950 950/1100	610 789	10/14 8/12	15/24 18/30	235/285 277/331	Forgings
1NiCrMo Steel	DIN 36CrNi Mo4	0.32 0.40	0.50 0.80	0.90 1.20	0.90 1.20	Mo 0.15 0.30	HT	100 4 250 10	880/1035 740/880	680 540	12 14	— —	— —	

2½NiCrMo Steel	Bs 826M40 (En26)	0.36 0.44	0.45 0.70	2.30 2.80	0.50 0.80	Mo 0.45 0.65	HT	100 4 250 10 100 4	1 550 925/1 075 1 550	123 740 1 235	7 12 7	11 28 33	444 269/331 444	Nitriding Nitriding Bright bar	
3NiCrMo Steel	BS 830M31 (En27)	0.27 0.35	0.45 0.70	2 75 3.25	0.90 1.20	Mo 0.25 0.35	HT	254 10 64 2½	850/1 000 1 080/1 240	650 940	13 11	41 41	— —		
4NiCrMo Steel	BS 835M30 (En30B)	0.26 0.34	0.45 0.70	3.90 4.30	1.10 1.40	Mo 0.20 0.35	HT	150 6	1 550	1 235	7	16	444		
4NiCrMo Steel	BS 2S146	0.34 0.42	0.15 0.60	3.50 4.50	1.60 2.00	Mo 0.60	HT	100 4	1 760/1 960	1 420	8	15	530	Ultra high strength aircraft steel	
¾CrMoV Steel	BS 897M39 (En40C) DIN 39Cr MoV139	0.35 0.43	0.45 0.70	— —	3.00 3.50	Mo 0.80 1.10 V 0.15 0.25	HT	63 2½	1 310	1 160	8	16	—	Nitriding steel Forgings	
5CrMoV	Bs BH11 ASTM A579 Grade 41	0.32 0.42	0.40	—	4.75 5 25	Si 0.85 1.15 Mo 1.25 1.75 V 0.30 0.50	HT	—	—	—	229 max	—	—	Tool steel	
1CrMoNiV Steel	ASTM A579 Grade 23 (D6AC)	0.45	0.75 (Typical)	0.55	1.05	Mo 1.00 V 0.10	HT	25 1	1 885 (Typical values	1 680 (Typical values)	10	Charpy V 20	—	Ultra high strength aircraft steel	
2NiCrMoV Steel	ASTM A579 Grade 32 (300M)	0.44	0.70 (Typical)	1.85	0.80	Si 1.60 Mo 0.35 V 0.06	HT	25 1 76 3	1 990 1 930 (Typical values)	1 685 1 620 (Typical values)	9 9	Charpy V 27 26	— —	Ultra high strength aircraft steel	
NiCrMoV Steel	UK Proprietary (NCMV)	0.44	0.45 (Typical)	1.80	1.50	Mo 0.90 V 0.25	HT	29 1⅛	2070 (Typical values)	1 700 (Typical values)	10	Charpy V 27	--	Ultra high strength aircraft steel	
1½CrAlMo Steel	BS 905M39 (En41B)	0.35 0.43	0.40 0.65	— —	1.40 1.80	Mo 0.15 0.25 Al 0.90 1.30	HT	63 2½ 150 6	850/1 000 700/850	680 525	13 17	42 50	248/302 201/255	Nitriding steel §	

* HT—Hardened and tempered.
§Surface hardness after Nitriding 950HV.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	British or other standard	Composition % C	Mn	Ni	Cr	Other elements	Condition*	Limiting ruling section mm	in	Properties (minima unless otherwise stated) UTS MPa	Yield stress MPa	Elong. (gl $5.65\sqrt{S_0}$) %	Impact J	Hardness HB	Remarks
1½CrAlMo Steel	DIN 41CrAlMo7	0.38 0.45	0.50 0.80	— —	1.50 1.80	Mo 0.25 0.40 Al 0.80 1.20	HT	102 152	4 6	930/1 125 835/1 035	740 635	12 14	— —	— —	Nitriding steel §
1½CrNiAlMo Steel	DIN 34CrAlNi Mo7	0.30 0.37	0.40 0.70	0.85 1.15	1.50 1.80	Mo 0.15 0.25 Al 0.80 1.20	HT	254	10	790/990	585	13	—	—	Nitriding steel §
1½MnNiCr Mo Steel	BS 945M38 (En100)	0.34 0.42	1.20 1.60	0.60 0.90	0.40 0.60	Mo 0.15 0.25	HT	29 250	1⅛ 10	1 000/1 150 700/850	850 495	12 15	42 28	293/352 201/255	Nitriding or bright bar
3¼NiCrMoV Steel	BS 976M33	0.28 0.38	0.20 0.60	2.90 3.60	0.90 1.70	Mo 0.45 0.65 V 0.08 0.15	HT	250 1 000	10 39	1 100/1 250 850/1 000	980 710	7/11 9/13	16/27 20/33	321/375 248/302	Forgings
4. *Carburizing steels* (BS 970:Part 1:1983; DIN 17210:1969)															
½Cr Steel	BS 523M15	0.12 0.18	0.30 0.60	— —	0.30 0.60	— —	OQ	19	¾	620	—	13	28	—	Case hardening
¾Cr Steel	Bs 527M17	0.14 0.20	0.70 1.00	— —	0.60 0.90	— —	OQ	19	¾	770	—	12	16	—	Case hardening
1¼MnCr Steel	DIN 16MnCr5	0.14 0.19	1.00 1.30	— —	0.80 1.10	— —	OQ	11 30	7/16 1 3/16	880/1 175 790/1 080	630 590	9 10	— —	— —	
1¼MnCr Steel	DIN 20MnCr5	0.17 0.22	1.10 1.40	— —	1.00 1.30	— —	OQ	11 30	7/16 1 3/16	1 080/1 375 990/1 280	740 680	7 8	— —	— —	
¾NiCr Steel	Bs 635M15 (En351)	0.12 0.18	0.60 0.90	0.70 1.10	0.40 0.80	— —	OQ	19	¾	770	—	12	27	—	

1NiCr Steel	BS 637M17	0.14	0.60	0.85	0.60	—	OQ	19	$\frac{3}{4}$	930	—	10	16	—	
	(En352)	0.20	0.90	1.25	1.00	—									
$1\frac{1}{2}$NiCr	DIN 15CrNi6	0.12	0.40	1.40	1.40	—	OQ	11	$\frac{7}{16}$	960/1 280	680	8	—	—	
Steel		0.17	0.60	1.70	1.70	—		30	$1\frac{3}{16}$	880/1 175	635	9	—	—	
$3\frac{1}{2}$NiCr	BS 655M13	0.10	0.35	3.00	0.70	—	OQ	19	$\frac{3}{4}$	1 000	—	9	35	—	
Steel	(En36A)	0.16	0.60	3.75	1.00	—									
4NiCr Steel	BS 659M15	0.12	0.25	3.90	1.00	Mo 0.15	OQ	19		1 310	—	8	28	—	Case hardening
	(En39B)	0.18	0.50	4.30	1.40	0.30									
$\frac{1}{2}$CrMo	DIN 20MoCr4	0.17	0.60	—	0.30	Mo 0.40	OQ	11	$\frac{7}{16}$	880/1 175	635	9		—	
Steel		0.22	0.90	—	0.50	0.50		30	$1\frac{3}{16}$	790/1 080	590	10	—	—	
$\frac{1}{2}$CrMo	DIN 25MoCr4	0.23	0.60	—	0.40	Mo 0.40	OQ	11	$\frac{7}{16}$	1 080/1 375	740	7	—	—	
Steel		0.29	0.90	—	0.60	0.50		30	$1\frac{3}{16}$	990/1 280	680	8	—	—	
$1\frac{1}{4}$NiMo	BS 655M17	0.14	0.35	1.50	—	Mo 0.20	OQ	19	$\frac{3}{4}$	770	—	12	35	—	Case hardening
Steel	(En34)	0.20	0.75	2.00	—	0.30									
$1\frac{1}{4}$NiMo	Bs 655M20	0.17	0.35	1.50	—	Mo 0.20	OQ	19	$\frac{3}{4}$	850	-	11	22	—	Case hardening
Steel		0.23	0.75	2.00	—	0.30									
$1\frac{1}{4}$NiMo	BS 665M23	0.20	0.35	1.50	—	Mo 0.20	OQ	19	$\frac{3}{4}$	930	–	10	13	—	Case hardening
Steel	(En35)	0.26	0.75		—	0.30									
$\frac{1}{2}$NiCrMo	BS 805M17	0.14	0.60	0.35	0.35	Mo 0.15	OQ	19	$\frac{3}{4}$	770	—	12	22	—	Case hardening
Steel	(En361)	0.20	0.95	0.75	0.65	0.25									
$\frac{1}{2}$NiCrMo	BS 805M20	0.17	0.60	0.35	0.35	Mo 0.15	OQ	19	$\frac{3}{4}$	850	—	11	16	—	Case hardening
Steel	(En362)	0.23	0.95	0.75	0.65	0.25									
$\frac{1}{2}$NiCrMo	BS 805M22	0.19	0.60	0.35	0.35	Mo 0.15	OQ	19	$\frac{3}{4}$	930	–	10	11	—	Case hardening
Steel		0.25	0.95	0.75	0.65	0.25									
$1\frac{1}{2}$NiCrMo	BS 815M17	0.14	0.60	1.20	0.80	Mo 0.10	OQ	19	$\frac{3}{4}$	1 080	—	8	22	—	Case hardening
Steel	(En353)	0.20	0.90	1.70	1.20	0.20									
$1\frac{1}{2}$NiCrMo	DIN 17CrNiMo6	0.14	0.40	1.40	1.50	Mo 0-25	OQ	11	$\frac{7}{16}$	1 175/1 420	835	7	—	—	Case hardening
Steel		0.19	0.60	1.70	1.80	0-35		30	$1\frac{3}{16}$	1 080/1 330	790	8	—	–	

*HT—Hardened and tempered. OQ—Oil quenched.
§Surface hardness after Nitriding 950HV.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
1¾NiCrMo Steel	BS 820M17 (En354)	0.14 0.20	0.60 0.90	1.50 2.00	0.80 1.20	Mo 0.10 0.20	OQ	19	¾	1 160	—	8	22	—	Case hardening
2NiCrMo Steel	BS 822M17 (En355)	0.14 0.20	0.40 0.70	1.75 2.25	1.30 1.70	Mo 0.15 9.25	OQ	19		1 310	—	8	22	—	Case hardening
3½NiCrMo Steel	BS 832M13 (En36C)	0.10 0.16	0.35 0.60	3.00 2.75	0.70 1.00	Mo 0.10 0.25	OQ	19	¾	1 080	—	8	28	—	Case hardening
4NiCrMo Steel	BS 835M15 (En39B)	0.12 0.18	0.25 0.50	3.90 4.30	1.00 1.40	Mo 0.15 0.30	OQ	19		1 310	—	8	28	—	Case hardening
5. *High alloy steels* *Stainless, heat resisting and valve steels* BS 970: Parts 1 and 4; 1449:Part 2; 1983, and Aircraft steels DIN 17224:1968; 17440:1967, Stahl-Eisen Werkstoffblatt 390:61, 400:60, 470:60, 670:69, AICMA (Association International des Constructeurs de Material Aerospacial) Standards															
Ferritic stainless and heat resisting steels															
12Cr Steel	BS 3361	0.12 max	1.00 max	1.00 max	11.5 13.5	—	HT	152	6	540/700	355	20	34	—	—
13Cr Steel	BS 403S17	0.08 max	1.00 max	0.50 max	12.0 14.0	—	S	51	2	420	200	20	—	121/183	B:F:P:Sh:St†
13CrSi Steel	DIN X10CrSi13	0.12 max	1.00 max	— —	12.0 14.0	Si 1.9 2.4	S	—	—	540/680	340	15	—	—	Scaling resistant up to 950°C in air
13CrAl Steel	BS 405S17	0.08 max	1.0 max	0.50 max	12.0 14.0	Al 0.10 0.30	S	51	2	420	200	20	—	121/183	P:Sh:St†
13CrAl Steel	DIN X10CrAl13	0.12 max	1.00 max	— —	12.0 14.0	Al 0.7 1.2	S	—	—	495/635	295	15	—	—	Scaling resistant up to 950°C in air
17Cr Steel	BS 430S17 (En60)	0.08 max	1.00 max	0.50 max	16.0 18.0	— —	S	63	2½	430	280	20	—	170 max	B:F:P:Sh:St†

17CrTi Steel	DIN X8CrTi17	0.10 max	1.0 max	— —	16.0 18.0	Ti 7 × C min	S	116	$\frac{5}{8}$	450/585	265	20	—	—	
17CrNb Steel	DIN X8CrNb17	0.10 max	1.00 max	— —	16.0 18.0	Nb 12 × C min	S	16	$\frac{5}{8}$	450/585	265	20	—	—	
17CrMo Steel	BS 434S17	0.08 max	1.00 max	0.50 max	16.0 18.0	Mo 0.90 1.30	S	—	—	430	245	20	—	—	Sh:St†
17CrMo Steel	DIN X6CrMo17	0.07 max	1.00 max	— —	16.0 17.5	Mo 0.90 1.20	S	16	$\frac{3}{8}$	450/635	295	25	—	—	
17CrMoTi Steel	DIN X8CrMoTi17	0.10 max	1.00 max	— —	16.0 18.0	Mo 1.50 2.00 7 × Ti C min	S	—	—	495/635	295	20	—	—	Used in the chemical and textile industries
18CrSi Steel	DIN X10CrSi18	0.12 max	1.00 max	— —	17.0 19.0	Si 1.90 2.40	S	—	—	540/680	340	15	—	—	Scaling resistant up to 1 050°C in air
18CrAl Steel	DIN X10CrAl18	0.12 max	1.00 max	— —	17.0 19.0	Al 0.70 1.20	S	—	—	495/635	295	12	—	—	Scaling resistant up to 1 050°C in air
24CrAl Steel	DIN Z10CrAl24	0.12 max	1.00 max	— —	23.0 25.0	Al 1.20 1.70	S	—	—	495/635	295	10	—	—	Scaling resistant up to 1200°C
29CrSi Steel	DIN X10CrSi29	0.12 max	1.00 max	— —	28.0 31.0	Si 1.00 2.00	S	— — —	— — —	540/680	385	12	—	—	Scaling resistant up to 1 150°C in air
16CrNiMo Nb Steel	UK (FV702)	0.03	0.60 (Typical)	2.5	16.0	Si 0.50 Mo 1.00 Nb 0.50	S	19	$\frac{3}{4}$	705 (Typical values)	500 (Typical values)	22	—	—	Resistant to stress corrosion
Martensitic stainless and heat resisting steels															
13Cr Steel	BS 410S21 (En56A)	0.09 0.15	1.00 max	1.00 max	11.5 13.5	— —	Ht	150 63	6 $2\frac{1}{2}$	550/700 700/850	370 525	20 15	34 34	152/207 201/255	B:F:P:Sh:St†

• OQ—Oil quenched. HT—Hardened and tempered. S—Softened.
† B = Bars. F = Forgings. P = Plates. Sh = Sheets. St = Strips.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
13CrS Steel	BS 416S21	0.09	1.50	1.00	11.5	(Mo 0.60 max)	HT	15	6	550/700	525	11	27	201/255	B:F† Free
	(En56AM)	0.15	max	max	13.5	S 0.15 0.30		63	2½	700/850					cutting steel
13CrSe Steel	BS 416S41	0.09	1.50	1.00	11.5	Mo 0.60 max	HT	150	6	550/700	370	15	34	152/207	B:F† Free
	(En56AM)	0.15	max	max	13.5	Se 0.15 0.30									cutting steel
13Cr Steel	BS 420S29	0.14	1.00	1.00	11.5	—	HT	150	6	700/850	525	15	27	201/255	B:F†
	(En56B)	0.20	max	max	13.5	—		29	1⅛	775/925	585	13	27	223/277	
13CrS Steel	BS 416S29	0.14	1.50	1.00	11.5	(0.60 max)	HT	152	6	700/850	525	11	27	201/255	B:F† Free
	(En56BM)	0.20	max	max	13.5	0.15 0.35		29		775/925	585	10	14	223/277	cutting steel
13Cr Steel	BS 3S62	0.18	1.00	1.00	12.0	—	HT	64	2½	700/850	525	15	34	201/255	—
		0.25	max	max	14.0	—		150	6	700/850	525	15	27	201/255	—
13Cr Steel	BS S124	0.15	1.50	1.00	12.0	Mo 0.60 max	HT	150	6	690/850	450	11	27	201/255	Free machining
		0.25	max	max	14.0	Zr 0.60 max Mo 1.00 max +Zr S 0.15/0.40									steel
13Cr Steel	BS 420S37	0.20	1.00	1.00	12.0		HT	150	6	775/925	585	13	13.5	223/277	B:F†
	(En56C)	0.28	max	max	14.0										
13CrS Steel	BS 416S37	0.20	1.50	1.00	12.0	(Mo 0.60 max)	HT	150	6	775/925	585	10	13.5	223/277	B:F Free
	(En56CM)	0.28	max	max	14.0	S 0.15/0.35									cutting steel
13Cr Steel	Bs 420S45	0.28	1.00	1.00	12.0	—	HT	150	6	770/930	585	13	13.5	—	B:F:Sh:St†
		0.36	max	max	14.0	—									
17CrNi Steel	BS 431S29	0.12	1.00	2.0	15.0	—	HT	150	6	850/1 000	680	11	20	—	B:F†
	(En57)	0.20	max	3.0	18.0	—									

17CrNiS Steel	BS 441S49	0.12 0.20	1.50 max	2.0 3.0	15.0 18.0	(Mo 0.60 max) S 0.15/0.30	HT	—	—	850/1 000	—	—	—	—	Free cutting steel round wire
17CrNiS Steel	BS 2S137	0.12 0.20	1.50 max	2.0 3.0	15.0 18.0	(Mo 0.60 max) S 0.15/0.30	HT	70	2¾	880/1 080	690	11	—	255/321	Primarily intended for nuts: free machining
17CrNiSe Steel	BS 441S49	0.12 0.20	1.50 max	2.00 3.00	15.0 18.0	(Mo 0.60 max) Se 0.15/0.30	HT	64	2½	850/1 000	—	—	—	—	Free cutting round wire
12CrMo Steel	DIN X19CrMo12.1	0.15 0.23	0.30 0.80	0.80 max	11.0 12.5	Mo 0.80/1.20	HT	152	6	680/835	495	16	—	—	B:F† Creep resistant
12CrMoV Steel	DIN X20CrMoV12.1	0.17 0.23	0.30 0.80	0.30 0.80	11.0 12.5	Mo 0.80/1.20 V 0.25/0.35	HT	19	¾	680/835	495	16	—	—	P:Sh:St:T† Creep reistant Resistant to high pressure H_2
12CrMoV Steel	DIN X22CrMoV12.1	0.20 0.26	0.30 0.80	0.30 0.80	11.0 12.5	Mo 0.80/1.20 V 0.25/0.35	HT	152	6	790/925	590	14	—	—	B:F† Creep resistant
12CrMoVNb Steel	AICME Fe-PM36 (UK FV448 Jethete 160)	0.11 0.19	0.20 1.25	0.50 1.20	10.0 12.0	Mo 0.40/1.00 V 0.10/0.70 Nb 0.10/0.60 +N	HT	530 dia 89 thick disc	21 dia 3½ thick disc	975 (Typical tangential values)	835	16	—	—	Gas turbine components
12CrNiMoV Steel	AICME Fe-PM37 (UK FV66 (+Nb) Jethete M152/M154	0.08 0.15	0.50 0.90	2.0 3.0	11.0 12.5	Mo 1.50/2.00 V 0.25/0.40 +N	HT	127 sq	5 sq	1 065 (Typical longitudinal values)	850	18	77	—	Gas turbine components
12CrCoMoV Nb Steel	AICME Fe-PM38 (UK FV535)	0.05 0.12	0.20 1.35	0.20 1.20	9.8 11.5	Co 5.00/7.50 Mo 0.50/1.10 V 0.10/0.60 Nb 0.20/0.60 +B	HT	560 dia 102 thick	22 dia 4 thick	1 065 (Typical tangential values)	925	17	—	—	Gas turbine components

* HT—Hardened and tempered.
† B = Bars. F = Forgings. P = Plates. Sh = Sheets. St = Strips. T = Tubes.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
Austenitic stainless and heat resisting steels															
12/12CrNi Steel	DIN X8CrNi 12 12 UK (FV DDq)	0.10 max	2.00 max	11.50 13.50	12.00 14.00	— —	S	—	—	495/635	200	50	—	—	Spoons and forks
14/10CrNi CuMoTi Steel	UK (FV467)	0.20	0.90	9.50 (Typical)	14-00	Mo 2.00 Cu 2.50 Ti 0.80	PH	—	—	680 (Typical values)	300 (Typical values)	52	135	—	B:F† Creep resistant
17/7CrNi Steel	BS 301S21	0.15 max	2.00 max	6.00 8.00	16.00 18.00	— —	S	—	—	540	215	40	—	220 max	Sh:St*. Also used as cold rolled strip or cold drawn wire for springs
18/8CrNi Steel	BS S205	0.15 max	0.50 2.00	7.50 9.00	17.0 19.0	— —	LT, HT	—	—	1 350/1 550 (Typical values)	—	—	—	—	Cold drawn and heat treated wire and springs
18/9CrNi Steel	BS 304S15 (En58E)	0.06 max	2.0 max	8.00 11.00	17.50 19.00	— —	HF or ST	—	—	480	230	40	—	183 max	B:F:Sh:St†
							CD	19	$\frac{3}{4}$	860	695	12	—	—	
								44	$1\frac{3}{4}$	650	310	28	—	—	
18/9CrNiN Steel	UK (Hi-proof 304)	0.06 max	2.00 max	8.00 11.00	17.50 19.00	N 0.15 0.25	S	102	4	585	295	35	—	—	B:P†
18/19CrNiTi Steel	Bs 2S129	0.08 max	0.50 2.00	8.00 11.00	17.00 19.00	Mo 1.00 max Ti 5 × C/0.8	S	150	6	540	210	35	69	183 max	
18/9CrNiNb Steel	BS 2S130	0.08 max	0.50 2.00	8.00 11.00	17.00 19.00	Mo 1.00 max Nb 10 × C/1.1	S	150	6	540	210	35	69	133 max	
18/9CrNiTi Steel	BS 321S12	0.08 max	0.50 2.00	9.00 12.00	17.00 19.00	Ti 5 × C/0.70	ST	19	$\frac{3}{4}$	540	277	40	—	149/217	
								5	2	508	246	40	—	137/201	
18/9CrNiS Steel	BS 303S21 (En58M)	0.12 max	1.00 2.00	8.0 11.0	17.0 19.0	S 0.15 0.30	ST	—	—	510	210	40	—	—	B:F† Free cutting
								19	$\frac{3}{4}$	860	695	12	—	—	
								44	$1\frac{3}{4}$	650	310	28	—	—	

18/10CrNi Steel	BS S536	0.03	0.50 2.00	9.0 12.0	17.5 19.0	—	S	73	500/700	190	40	—	--	Sh:St†
18/10CrNi Steel	BS 304S12	0.03 max	0.50 2.00	9.0 12.0	17.5 19.0	—	ST	51 2	493	231	40	-	134/192	—
18/10CrNi N Steel	UK (Hi-proof 304L)	0.03 max	2.00 max	9.0 12.0	17.5 19.0	N 0.15 0.25	S	102 4	585	295	35	—	–	B:F†
18/10CrNi Steel	BS 304S15 (En58E)	0.06 max	2.00 max	8.0 11.0	17.5 19.0	—	S	160 --	480	230	40	—	183 max	Sh:St*
18/10CrNiTi Steel	BS S524, S526	0.08	0.50 2.00	9.0 11.0	17.0 19.0	Ti 5 × C/0.70	CR S	3 3	800/1 100 540	640 210	15 30	35	179 max	Sh:St†
18/10CrNiNb Steel	BS S525, S527	0.08	0.50 2.00	9.0 11.0	17.0 19.0	Nb 10 × C/1.0	S	1.5 3.0	540 540	210 210	30 40	— —	— —	Sh:St†
18/11CrNi Steel	BS 305S19	0.10 max	2.00 max	11.0 13.0	17.0 19.0	—	S	— —	460	185	40	—	185 max	Sh:St†
17/10CrNi Mo Steel	BS 315S16	0.07 max	2.00 max	9.0 11.0	16.5 18.5	Mo 1.25 1.75	S	— --	510	205	40	-	205 max	B:F:Sh:St†
17/10CrNi MoNb Steel	UK (FV548)	0.08	1.00	11.5 (Typical)	16.5	Mo 1.5 Nb 1.0	S	– —	600 (Typical values)	225 (Typical values)	55	135	—	B:F† Creep resistant
17/11CrNi MoSe Steel	BS 326S36	0.08 max	0.50 2.00	10.0 13.0	16.5 18.5	Mo 2.25 3.00 Se 0.15 0.30	S	— -	510	210	40	—	—	B:F† Free cutting
17/12CrNi Mo Steel	BS 316S12	0.03 max	0.50 2.00	11.0 14.0	16.5 18.5	Mo 2.25 3.00	ST	51 2	508	246	40	—	137/201	B:F:P:Sh:St†
17/12CrNi MoN Steel	UK (Hi-proof 316L)	0.03 max	2.00 max	11.0 14.0	16.5 18.5	Mo 2.25 3.00 N 0.15 0.25	S	102 4	620	315	35	—	—	B:F†

*S—Softened. PH—Precipitation hardened. LT—Low temperature. HT—Heat treatment. CR—Cold rolled.
†B = Bars. F = Forgings. P = Plates. Sh = Sheets. St = Strips. T = Tubes.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_o}$) %	*Impact* J	*Hardness* HB	*Remarks*
17/12CrNi Mo Steel	BS 316S16	0.07 max	0.50 2.00	10.0 13.0	16.5 18.5	Mo 2.25 3.00	ST	52 19 44	2 $\frac{3}{4}$ $1\frac{3}{4}$	524 860 650	262 695 310	40 12 28	— — —	143/212 — —	B:F:P:Sh:St† Also used cold rolled strip or wirre for springs
17/12CrNi MoN Steel	UK (Hi-proof 316)	0.07 max	2.00 max	10.00 13.0	16.5 18.5	Mo 2.25 3.00 N 0.15 0.25	S	102	4	620	315	35	—	—	B:F†
17/12CrNi MoTi Steel	BS 320S17	0.08 max	0.50 2.00	11.0 14.0	16.5 18.5	Mo 2.25 3.00 Ti 4 × C/0.60	ST	52	2	524	270	40	—	143/212	B:F:P:Sh:St†
18/12 CrNiMo Nb Steel	BS (En58J-Nb) DIN X10CrNiMoNb 18 12	0.10 max	2.00 max	12.0 14.5	16.5 18.5	Mo 2.5 3.0 Nb 8 × C min	S	64	$2\frac{1}{2}$	495/749	225	40	—	—	B:F:P:Sh:St†
16/13CrNi Nb Steel	DIN X8CrNiNb 1613	0.04 0.10	1.5 max	12.0 14.0	15.0 17.0	Nb 10 × C/1.2	S	152	6	510/680	200	35	—	—	Creep reistant
16/13CrNi MoVNb Steel	DIN X8CrNiMo VNb 1613	0.04 0.10	1.5 max	12.5 14.5	15.5 17.5	Mo 1.1 1.5 V 0.60 0.85 Nb 10 × C/1.2 + N	PH	152	6	540/740	255	30	–	—	Creep resistant. Resistant to high pressure hydrogen
16/16 CrNiMo Nb Steel	DIN X8CrNi MoNb 1616	0.04 0.10	1.50 max	15.5 17.5	15.5 17.5	Mo 1.6 2.0 Nb 10 × C/1.2	S	152	6	525/680	215	35	—	—	Creep resistant

16/16CrNiW Nb Steel	DIN X6CrNiW Nb Steel	0.04 0.10	1.50 max	15.5 17.5	15.5 17.5	W 2.5 3.5 Nb 10 × C/1.2 + N	S	152	6	540/740	255	30		—	Creep resistant
16/16CrNi MoNbB Steel	DIN X8CrNiMo NbB 1616	0.04 0.10	1.50 max	15.5 17.5	15.5 17.5	Mo 1.6 2.0 Nb 10 × C/1.2 B 0.05 0.10	PH	152	6	540/740	280	30	—	—	Nuclear reactor components
18/15CrNi Mo Steel	BS 31S12	0.03 max	2.00 max	14.0 17.0	17.5 19.5	Mo 3.0 4.0	S	—	—	490	195	40	—	195 max	B:F:P:Sh:St†
18/13CrNi Mo Steel	BS 317S16	0.06 max	2.00 max	12.0 15.0	17.5 19.5	Mo 3.0 4.0	S	—	—	510	205	40	—	205 max	B:F:P:Sh:St†
20/18NiCr MoCuNb Steel	DIN X5CrNiMo CuNb 18 18	0.07 max	2.00 max	19.0 21.0	16.5 18.5	Mo 2.0 2.5 Cu 1.8 2.2 Nb 8 × C min	S	—	—	495/740	225	40	—	—	Resistant to sulphuric acid
20/12CrNiSi Steel	DIN X15CrNiSi 2012	0.20 max	2.00 max	11.0 13.0	19.0 21.0	Si 1.8 2.3	S	—	—	585/740	295	40	—	—	Resistant to scaling up to 1 050°C in air
23/14CrNi Steel	BS 309S24, S522	0.15 max	2.00 max	13.0 16.0	22.0 25.0	—	S	—	—	510	205	40		205 max	P:Sh:St†
23/14CrNiTi Steel	BS S125, S528	0.15 max	0.50 2.00	13.0 16.0	22.0 25.0	Ti 4 × C min	ST	152	6	540	215	28	68		B:F:Sh:St†
23/14CrNi Nb Steel	BS S126, S529	0.15 max	0.50 2.00	13.0 16.0	22.0 25.0	Nb 8 × C min	ST	152	6	540	215	28	68	—	B:F:Sh:St†
24/17CrNiTi Steel	BS S127, S530	0.12 max	0.50 2.00	16.0 19.0	23.0 26.0	Ti 5 × C/0.90	S	152	6	540	210	30	—	179 max	B:F:Sh:St*

*S—Softened. PH—Precipitation hardened.
†B = Bars. F = Forgings. P = Plates. Sh = Sheets. St = Strips. T = Tubes.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
24/17CrNi Nb Steel	BS S128, S531	0.12 max	0.50 2.00	13.0 16.0	23.0 26.0	Nb 10 × C/1.40	S	152	6	540	210	30	—	179 max	B:F:Sh:St†
24/20CrNi Steel	BS 310S24	0.15 max	2.00 max	19.0 22.0	23.0 26.0	- —	S	—	—	510	205	40	—	205 max	B:F:Sh:St† Resistant to scaling up to 1050°C in air
25/15NiCr TiMoVA1B Steel	AICMA FE-PA92HT (UK FV559 ASTM A286)	0.08 max	1.00 2.00	24.0 27.0	13.5 16.0	Si 0.4/1.0 Ti 1.9/2.3 Mo 1.0/1.5 V 0.1/0.5 Al 0.35 max +B	PH	—	—	900	590	20	—		Gas turbine components. Also suitable for use at sub-zero temperatures
25/20CrNiSi Steel	DIN X15CrNiSi 2520	0.20 max	2.00 max	19.0 21.0	24.0 26.0	Si 1.8 2.3	S	—	—	590/740	295	40	—	—	Scaling resistant up to 1200°C in air
25/25 CrNiMoTi Steel	DIN XSCrNiMoTi 2525	0.06 max	2.00 max	24.0 26.0	24.0 26.0	Mo 2.0 2.5 Ti 5 × C min	S	—	—	500/740	225	35	—	—	Used in the chemical industry
36/16NiCrSi Steel	DIN X12NiCrSi 3616	0.15 max	2.00 max	34.0 37.0	15.0 17.0	Si 1.5 2.0	S	—	—	540/740	260	40	—	—	Resistant to scaling up to 1100°C in air
41/12 NiCrMo TiCoAl B Steel	AICMA FE-PA99-HT	0.10 max	0.50 max	40.0 45.0	11.0 14.0	Mo 5.0/6.5 Ti 2.6/3.1 Co 1.0 max Al 0.35 max +B	PH	—	—	1130	820	10	—	—	Gas turbine components

20/20/20 CrNiCoMo WNbN Steel	AICMA FE-PA91-HT	0.08 0.16	1.00 2.00	19.0 21.0	20.0 22.5	Co 18.5/21.0 Mo 2.5/3.5 W 2.0/3.0 Nb 0.75/1.25 N 0.10/0.20	PH	—	—	680/960	340	30			Gas turbine components
12/11/6 CrNiMn Steel	DIN X15CrNiMn 12 10	0.05 0.20	5.5 6.5	9.0 11.0	10.5 12.5	— —	S CF	— —	— —	500/650 630/835	220 500	45 35	—	—	
15/10/6 CrNiMn-MoNbVb Steel	UK (Esshete 1250)	0.15 max	5.5 7.0	9.0 11.0	14.0 16.0	Mo 0.8/1.2 Nb 0.75/1.25 V 0.15/0.40 +B	S	—	—	495	180	30	—	—	Pressure vessel plate, superheater tube, steam piping. Creep resistant
17/6/4 CrMnMiN Steel	AISI 201	0.15 max	5.5 7.5	3.5 5.5	16.0 18.0	N 0.25 max	S	—	—	790 (Typical values)	380 (Typical values)	40	—	—	
17/8/5 CrMnNiM Steel	BS 284S16	0.07 max	7.00 10.00	4.0 6.5	16.5 18.5	N 0.15 0.25	S	—	—	630	300	40	—	200 max	P:Sh:St†
18/9/5 CrMnNiN Steel	AISI 202 DIN X8 CrMnNi 18 8	0.15 max	7.5 10.0	4.0 6.0	17.0 19.0	N 0.25 max	S	—	—	725 (Typical values)	380 (Typical values)	48	—	—	
18/8/6 CrMnNiN Steel	DIN X7CrMnNiN 18 8	0.07	8.9	5.9 (Typical)	18.0	Mo 0.30 N 0.22	S	—	—	718 (Typical values)	370 (Typical values)	55		—	Used in the chemical industry
18/10/9 CrMnNi-MoN Steel	DIN X3CrMnNi-MoN 18 10	0.04	11.0	9.0 (Typical)	19.0	Mo 2.35 N 0.30	S	—	—	820	430	38	—	—	Used in the chemical industry
18/12/2 MnCrNi-Mo Steel	DIN X12MnCr 18 12	0.15 max	17.0 19.0	1.5 2.5	11.0 13.0	Mo 0.30 0.80 P 0.08 max	S CF	— —	— —	630/790 790/990	295 500	45 25	—		Used in the cutlery industry

*S—Softened. PH—Precipitation hardened. CF—Cold formed.
†B—Bars. F—Forgings. P—Plates. Sh—Sheets. St—Strips. T—Tubes.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	British or other standard	Composition % C	Mn	Ni	Cr	Other elements	Condition[a]	Limiting ruling section mm	in	Properties (minima unless otherwise stated) UTS MPa	Yield stress MPa	Elong. (gl $5.65\sqrt{S_0}$) %	Impact J	Hardness HB	Remarks
Austenitic-ferritic stainless and heat resisting steels															
25/5CrNi Steel	Swedish (UHB 45) AISI 327	0.10 max	Not given (Typical)	4.8	25.5	–	S	—	—	630 (Typical values)	460 (Typical values)	30	—	—	Resistant to scaling up to 1075°C in air
25/4CrNiSi Steel	DIN X20CrNiSi 25 4	0.15 0.25	2.0 max	3.5 5.5	24.0 26.0	Si 0.8 1.3	S	—	—	590/740	390	26	—		Resistant to scaling up to 1100°C in air
25/CrNiMo Steel	Swedish (UHB44) AISI 329	0.08	Not given (Typical)	5.3	25.0	Mo 1.50	S	—	—	660 (Typical values)	500 (Typical values)	30	—		Used in the chemical industry. Scaling resistant up to 1075°C in air
Valve steels (BS 970:Part 4:1970, Stahl Eisen Werkstoffblatt 490–52)															
9CrSi Steel	BS 401S45 (En52)	0.40 0.50	0.30 0.75	0.50 max	7.5 9.5	Si 3.00 3.75	HT	—		925 (Typical values)	680 (Typical values)	22	—	255	
14/14CrNiW Steel	BS 331S40 (En54)	0.35 0.50	0.50 1.00	12.0 15.0	12.0 15.0	Si 1.0/2.0 W 2.0/3.0	S	—		895 (Typical values)	510 (Typical values)	23	—	—	
14/14CrNi WMo Steel	BS 331S42, S111 (En54A)	0.37 0.47	0.50 1.00	13.0 15.0	13.0 15.0	Si 1.0/2.0 W 2.2/3.0 Mo 0.40/0.70	S	—	—	—	—	—	20	—	
18/9 CrNiWSi Steel	DIN X45CrNiW 189 (Similar to BS En55)	0.40 0.50	0.80 1.50	8.00 10.0	17.0 19.0	Si 2.0/3.0 W 0.8/11.2	AH	—	—	790/990	390	25	—	—	Resistant to lead oxide corrosion
20CrNiSi Steel	BS 443S65 (En59)	0.75 0.85	0.30 0.75	1.20 1.70	19 0 21.0	Si 1.75 2.25	HT	—	—	895/1 050 (Typical values)	710	7	—	269	

21/11CrNiSi Steel	BS 381S34	0.15 0.25	1.50 max	10.5 12.5	20.0 22.0	Si 0.75/1.25 N 0.15/0.30	PH	—	—	—	—	—	—	197	Resistant to lead oxide corrosion	
21/9/4 CrMnNiN Steel	BS 349S52	0.48 0.58	8.0 10.0	3.25 4.50	20.0 22.0	N 0.38/0.50 C+N 0.90 min	PH	—	—	1 050 (Typical values)	620 (Typical values)	9	—	321/352 C+Ni 0.92 min	Resistant to lead oxide corrosion	
21/9/4 CrMnNi-NS Steel	BS 349S54	0.48 0.58	8.0 10.0	3.25 4.50	20.0 22.0	N 0.38/0.50 S 0.035 0.080 C+N 0.90 min	PH	—	—	1 050 (Typical values)	620 (Typical values)	8	—	321/352 C+Ni 0.92 min	Free cutting steel	
21/9/4 CrMnNiNNb Steel	BS 352S52	0.48 0.58	8.00 10.00	3.25 4.50	20.0 22.0	N 0.38/0.50 Nb 2.00/3.00 C+N 0.90 min		—	—	—	—	—	—	285		
21/9/4 CrMnNiNNb S Steel	BS 352S54	0.48 0.58	8.00 10.00	3.25 4.50	20.0 22.0	N 0.38/0.50 Nb 2.00/3.00 S 0.035 0.080 C+N 0.90 min		—	—	—	—	—	—	—	Free cutting steel	
23/5 CrNiMo Steel	DIN X45CrNi Mo 23 5	0.40 0.50	0.90 1.20	4.5 5.5	22.0 24.0	Si 1.0 1.3 Mo 2.5 3.0	PH	—	—	1 235 (HRC40)	—	—	—	—		
High-strength stainless steels (ASTM A579-67, DIN 17224:1968) *Semi-Austenitic steels (Typical compositions and mechanical properties)*																
17/7CrNiAl Steel	AISI 631 ASTM A579 Grade 62 (17/7PH) DIN X7CrNiAl 177	0.07	0.8	7.0	17.0	Al 1.2	PH	—	—	1 360	1 250	10	—	—	Sheet and strip. Also used as cold-rolled strip or cold-drawn wire for springs at temperatures up to 350°C	

*S—Softened. HT—Hardened and tempered. AH—Age hardened. PH—Precipitation hardened.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
15/7CrNi-MoAl Steel	AISI 632 ASTM A579 Grade 63 (PH15/7Mo)	0.07	0.8	7.1	15.1	Mo 2.2 Al 1.2	PH	—	—	1 515	1 420	9	—	—	Pressure vessels, springs
14/5CrNiCu MoNb Steel	BS S145 (FV520B)	0.07	1.00	5.8	14.5	Mo 1.6 Cu 1.6 Nb 0.30	PH	—	—	1 470	1 030	10	20	—	Bars and forgings for aircraft parts
14/8CrNiMo Al Steel	USA (PH14/8Mo)	0.04	0.6	8.3	15.1	Mo 2.2 Al 1.2 +N	PH	—	—	1 570	1 450	8	—	—	Pressure vessels, aircraft parts
16/4CrNi-MoN Steel	AISI 633 (AM 350)	0.10	0.8	4.25	16.5	Mo 2.75 N 0.10	PH	—	—	1 405	1 175	11	Charpy V 20	—	Valves, piping, aircraft parts
15/4CrNi MoN Steel	AISI 634 ASTM A579 Grade 64 (AM 355)	0.13	0.8	4.25	15.5	Mo 2.75 N 0.10	PH	—	—	1 480	1 250	11	Charpy V 20	—	Aircraft parts, valves, turbine parts
15/5CrNi-CuMoTi Steel	BS S533 (FV520S)	0.05	1.3	5.5	16.0	Mo 1.8 Cu 2.00 Ti 0.10	PH	—	—	1 370	980	11	—	—	Sheet and strip for aircraft parts
Martensitic steels															
17/4CrNiCu Nb Steel	AISI 630 ASTM A579 Grade 61 (17/4PH)	0.04	0.8	4.3	16.0	Cu 3.3 Nb 0.27	PH	—	—	1 360	1 265	12	—	—	Gears, springs, cutlery, aircraft parts, turbine components
15/5CrNi CuNb Steel	USA(15/5PH)	0.04	0.8	4.6	15.0	Cu 3.3 Nb 0.27	PH	—	—	1 360	1 265	12	—	—	Gears, cams, cutlery, aircraft parts

13/8CrNi-MoAl Steel	USA(PH13/8Mo)	0.03	0.10 max	8.2	12.8	Mo 2.2 Al 1.1 +N	PH	76	3	1465	1310	12	—	—	Aircraft parts, fasteners, shafts
12/8CrNi-CuTiNb Steel	USA(Custom, 455)	0.03	0.25	8.5	11.7	Cu 2.2 Ti 1.2 Nb 0.3	PH	102	4	1420	1345	10	Charpy V 16	—	Fasteners, springs, pressure vessels, valve parts, forgings
14/13CrCoV Steel	USA(AFC77)	0.15	0.20	—	14.5	Co 13.0 Mo 5.0 V 0.40	PH	—	—	1630	1295	10	—	—	Die casting dies, glass moulds
14/15CrCo-NiMoTi Steel	USA(AM367)	0.02	Not given	3.5	14.0	Co 15.0 Mo 2.0 Ti 0.4	PH	—	—	1500	1465	11	—	—	Bars, forgings, sheet and strip
12/12CrCo-NiMoTiNb Steel	UK(D70)	0.02	Not given	4.0	12.0	Co 12.0 Mo 4.0 Ti 0.40 Nb 0.10 Al 0.10 +Zr, B	PH	—	—	1650	1600	9.5	16	—	Bars, forgings, sheet and strip
12/8/5CrNi-CoMoTi Steel	WG(Ultrafort 401)	0.01	Not given	8.1	12.6	Co 5.2 Mo 2,0 Ti 0.80 +Al, Zr, B	PH	—	—	1650	1570	11	—	—	Pressure vessels, springs, fasteners, aircraft parts, extrusion and stamping tools
Maraging nickel steels (ASTM A579-67) *Typical compositions*															
12/5NiCr-MoAlTi Steel	ASTM A579 Grade 75	0.02	Not given	12.0	5.0	Mo 3.0 Al 0.40 Ti 0.20	PH	—	—	1310 (Typical values)	1250 (Typical values)	15	Charpy V 74	—	Gears, fasteners, shafts, rocket and missile cases, aircraft parts, plastic mould dies, die holders, die casting die inserts, extrusion tools

* PH—Precipitation hardened.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
18/8NiCo-MoTi Steel	ASTM A579 Grade 71	0.01	Not given	18.0	—	Co 8.5 Mo 3.0 Ti 0.20 Al 0.10 +Ca, Zr, B	PH	—	—	1 390/1 540	1 330/1 480	9/13	Charpy V 34/68	—	Gears, fasteners, shafts, rocket and missile cases, aircraft parts, plastic mould dies, die holders, die casting die inserts, extrusion tools
18/8NiCo MoTi Steel	ASTM A579 Grade 72	0.01	Not given	18.0	—	Co 8.0 Mo 5.0 Ti 0.40 Al 0.10 +Ca, Zr, B	PH	—	—	1 680/1 910	1 60/1 820	8/10	Charpy V 20/41	—	Gears, fasteners, shafts, rocket and missile cases, aircraft parts, plastic mould dies, die holders, die casting die inserts, extrusion tools
18/8NiCo-MoTi Steel	ASTM A579 Grade 73	0.01	Not given	18.0	—	Co 9.0 Mo 5.0 Ti 0.60 Al 0.10 +Ca, Zr, B	PH	—	—	1 820/2 130	1 790/2 090	6/9	Charpy V 14/27	—	Gears, fasteners, shafts, rocket and missile cases, aircraft parts, plastic mould dies, die holders, die casting die inserts, extrusion tools
Other high alloy steels (BS 1501: Part 2:1988, 1503:1969, Stahl Eisen Werkstoffblatt 390-61, ASTM 579-67)															
12Mn Steel	DIN X120Mn12	1.1 1.3	11.5 13.5	— —	— —	P 0.1 max	S	—	—	790/1 080	340	40	—	—	Non-magnetic
18Mn Steel	DIN X35Mn18	0.30 0.40	17.0 19.0	— —	— —	P 0.1 max	S	—	—	680/930	250	30	—	—	Non-magnetic

18MnCr Steel	DIN X40MnCr18	0.30 0.50	17.0 19.0	— —	3.0 3.5	P 0.1 max	S CF	— —	— —	740/930 990/1 175	295 880	45 20	— —	— —	Non-magnetic end bells for alternator rotors
23MnCr Steel	DIN X40MnCr23	0.30 0.50	21.0 24.0	— —	3.0 3.5	P 0.1 max	S	—	—	680/880	310	45	—	—	Non-magnetic
9Ni Steel	BS 1501-510	0.10 max	0.30 0.80	8.5 9.75	0.30 max	Mo 0.10 Al 0.015 0.055 Cu 0.30	QT	—	50	690	540	18	—	—	Pressure vessel plates
13Cr Steel	UK (Silver Fox 67)	0.60 0.70	0.50 1.0	— —	12.0 13.5	— —	A LR	— —	— —	770 1 080	500 1 050	18 3	— —	— —	Razor and surgical blades, general cutting tools
9/4NiCoCr-MoV Steel	USA(HP9-4-20)	0.20	0.30 (Typical)	9.2	0.8	Co 4.5 Mo 1.0 V 0.10	HT	—	—	1 420 (Typical values)	1 235 (Typical values)	14	Charpy V 74	—	Rocket motor cases, seamless tubing, shafts, pressure vessels, piping
9/4NiCo CrMoV Steel	ASTM A579 Grade 81 (HP9-4-25)	0.25	0.25 (Typical)	8.0	0.45	Co 4.0 Mo 0.45 V 0.10	HT	152	6	1 375 (Typical values)	1 265 (Typical values)	13	Charpy V 47	—	Rocket motor cases, seamless tubing, shafts, pressure vessels, piping
9/4NiCoCr MoV Steel	ASTM A579 Grade 82 (HP9.4.30)	0.39	0.25 (Typical)	7.5	1.0	Co 4.5 Mo 1.0 V 0.10	HT	126	5	1 570 (Typical values)	1 375 (Typical values)	11 —	Charpy V 34	—	Armour plate aircraft parts
9/4NiCo-MoV Steel	ASTM A579 Grade 83 (HP9-4-45)	0.45	0.25 (Typical)	7.5	0.30	Co 4.0 Mo 0.30 V 0.10	Salt bath quenched	76	3	1 850	1 540	9	Charpy V 27	—	Aircraft parts, fasteners, connecting rods, valve-spring wires
							Hardened, subzero cooled and tempered	76	3	1 990 (Typical values)	1 710 (Typical values)	7	20		

* PH—Precipitation hardened. S—Softened. CF—Cold formed. QT—Double normalized and tempered, or, hardened and tempered. A—Annealed. LR—Lightly rolled. HT—Hardened and tempered.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*Impact* J	*Hardness* HB	*Remarks*
6. *Spring steels* (BS 970:Part 1:1983, DIN 17221:1955, 17222:1955, 17225:1955) *Carbon steels (cold rolled strip except for 060 A96)*															
0.52C Steel	BS 080A52 (En43C) DIN Ck53	0.50 0.55	0.70 0.90	— —	— —	Si 0.10 0.35	HT	—	—	1 175/1 390	1 035	7	—	—	Laminated springs
0.67C Steel	BS 080A67 (En43E) DIN Ck67	0.65 0.70	0.70 0.90	— —	— —	Si 0.10 0.35	S	—	—	—	—	—	—	229 max	Laminated springs
0.72C Steel	BS 070A72 (En42)	0.70 0.75	0.60 0.80	— —	— —	Si 0.10 0.35	HT	—	—	—	—	—	—	—	Laminated springs
0.78C Steel	DIN Mk75	0.75 0.82	0.60 0.80	— —	— —	Si 0.10 0.35	HT	—	—	1 575/1 775	1 465	6	—	—	Laminated springs
0.96C Steel	DIN Mk101	0.93 1.00	0.50 0.70	— —	— —	Si 0.10 0.35	HT	—	—	1 760/2 315	1 670	5	—	—	Coil springs up to 25 mm (1 in)
Manganese and manganese silicon steels															
2Mn Steel	DUN 50Mn7	0.45 (Typical	1.80	—	—	—	HT	—	—	1 175/1 390	1 030	7	—	—	Laminated springs
1¾Si Steel	DIN 46Si7	0.42 0.50	0.50 0.80	— —	— —	Si 1.5 1.8	HT	—	—	1 280/1 465	1 080	6	—	—	Elliptic or helical springs, laminated springs
2Si Steel	DN 51Si7	0.50 0.57	0.70 1.00	— —	— —	Si 1.70 2.10	HT	—	—	1 280/1 465	1 080	6	—	—	Laminated springs, coil springs up to 25 mm (1 in) bar dia.

2Si Steel	DIN 55Si7	0.55 0.62	0.70 1.00	— —	— —	Si	1.70 2.10	HT	—	—	1 280/1 465	1 080	6	—	—	Laminated springs, coil springs up to 25 mm (1 in) bar dia.
2Si Steel	DIN 66Si7	0.58 0.65	0.70 1.00	— —	— —	Si	1.70 2.10	HT	—	—	1 375/1 540	1 175	6	—	—	Laminated springs, coil springs over 25 mm (1 in) bar dia.
1SiMn Steel	DIN 60SiMn5	0.55 0.65	0.90 1.10	— —	— —	Si	1.0 1.3	HT	—	—	1 330/1 540	1 030	6	—	—	Laminated springs, ring springs
Low alloy steels (hot rolled)																
1¾MnV Steel	DIN 50MnV7	0.50 (Typical)	1.70	—	—		0.10	HT	—	—	1 280/1 465	1 130	7		—	Laminated springs, coil springs up to 25 mm (1 in) bar dia.
1¼SiCr Steel	DIN 67SiCr5	0.62 0.72	0.40 0.60	— —	0.40 0.60	Si	1.2 1.4	HT	—	—	1 465/1 690	1 330	5	—	—	Coil springs and valve springs. Used up to 300°C
1CrV Steel	BS 735A50 (En47) DIN 50CrV4	0.46 0.54	0.60 0.90	— —	0.80 1.10	V Si	0.15 min 0.10 0.35	HT	2.8	—	1 685/1 835	—	—	—	—	Round spring wire
1CrV Steel	DIN 58CrV4	0.55 0.62	0.80 1.10	— —	0.90 1.20	V	0.07 0.12	HT	—	—	1 465/1 690	1 330	6	—	—	Torsion bars over 40 mm (1⅝ in) bar dia.
1CrMo Steel	DIN 50CrMo4	0.50 (Typical)	0.90	—	1.0	Mo	0.20	HT	—	—	1 330/1 540	1 175	6		—	Laminated springs, coil springs

* HT – Hardened and tempered. S – Softened.

Table 22.47 FORGED OR ROLLED STEELS—ROOM TEMPERATURE LONGITUDINAL MECHANICAL PROPERTIES—*continued*

Material	*British or other standard*	*Composition %* C	Mn	Ni	Cr	*Other elements*	*Condition**	*Limiting ruling section* mm	in	*Properties (minima unless otherwise stated)* *UTS* MPa	*Yield stress* MPa	*Elong.* (g) $5.65\sqrt{S_o}$ %	*Impact* J	*Hardness* HB	*Remarks*
¼NiCrMo Steel	BS 805A60	0.55 0.65	0.65 1.05	0.40 0.70	0.35 0.75	Mo 0.15 0.25 Si 0.15 0.40	HT	—	—	—	—	—	—	—	Hot formed springs
2SiCrMo Steel	BS925A60	0.55 0.65	0.70 1.00	— —	0.20 0.40	Si 1.70 2.10 Mo 0.20 0.30	HT	—	—	—	—	—	—	—	Hot formed springs
1CrMoV Steel	DIN 51CrMoV4	0.51 (Typical)	0.90	—	1.0	Mo 0.20	HT	—	—	1 465/1 690	1 330	6	—	—	Torsion bars over 40 mm ($1\frac{9}{16}$ in) bar dia.
1¼CrMoV Steel	DIN 45CrMoV67	0.40 0.50	0.60 0.80	— —	1.3 1.5	Mo 0.65 V 0.75 0.25 0.35	HT	—	—	1 390/1 690	Not given	Not given	—	—	Used up to 450°C
2¼CrWV Steel	DIN 30WCrV179	0.25 0.35	0.20 0.40	— —	2.2 2.5	W 4.0 4.5 V 0.50 0.70	HT	—	—	1 390/1 690	Not given	Not given	—	—	Used up to 500°C
High alloy steel															
8WCrMoV Steel	DIN 65WMo348	0.63 0.68	0.30 appr	— —	3.5 4.0	W 8.0 9.0 Mo 0.80 0.90 V 0.60 0.80	HT	—	—	1 390/1 690	Not given	Not given	—	—	Used up to 550°C

* HT—Hardened and tempered.

Table 22.44a MICROALLOYED CARBON MANGANESE STEELS—BS 970:PART 1:1983 FOR MECHANICAL AND ALLIED ENGINEERING PURPOSES

BS Standard grade	*Composition %* C	Si	Mn	P and S max	*Others*	*Heat treatment*	*Limiting ruling section* mm	in	*UTS* MPa	*Yield* MPa	*Elong.* (gl $5.65\sqrt{S_0}$)	*Impact* KCV J	*Hardness* HB
280M01	0.30/0.55	0.15/0.60	0.60/1.50	P 0.35 S 0.045/0.065	V 0.08/0.20 Al 0.035 max	S	100	4	775/925	530	14	10	223/277
						T	100	4	850/1 000	560	12	8	248/302
						U	100	4	925/1 075	600	10	8	269/331

Notes:

1. May be supplied with higher S to improve machinability.
2. Other micro-alloying additions such as Nb or Ti may be made either singly or in combination, in which case the total determined by product analysis shall be in the range 0.08–0.20%.
3. Whilst the tensile strengths indicated by S, T, U, are identical with type of through hardened and tempered steels they are not achieved by hardening and tempering. It should be noted that the other properties of these steels may differ from type for the hardened and tempered steels.

Table 22.48 TYPICAL HOT TENSILE PROPERTIES OF FORCED OR ROLLED STEELS IN THE LONGITUDINAL DIRECTION

		Typical composition "$_0$						*Tensile properties*				
Material	*British or other standards*	C	Mn	Ni	Cr	*Other elements*	*Condition*	*Temperature* °C	*UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*RA* %
1. *Carbon steels*												
Armco Iron	—	0.02	0.03	—	—	—	Normalized	RT	340	185	39	69
								200	448	185	23	54
								400	309	Not given	15	67
0.15C Steel	BS 040A12 (En2B)	0.13	0.50	—	—	—	Normalized	RT	417	247	33	Not given
								200	463	232	23	Not given
								400	386	193	33	Not given
								500	309	Not given	33	Not given
0.20C Steel	BS 070M20 (En3)	0.20	0.70	—	—	—	Normalized	RT	448	263	30	62
								200	463	224	24	54
								400	371	185	31	67
0.25C Steel	BS 070M26 (En4)	0.26	0.70	—	—	—	Normalized	RT	479	247	30	Not given
								200	510	232	22	Not given
								400	448	201	27	Not given
								500	340	185	28	Not given
0.35C Steel	BS 080M36	0.36	0.80	—	—	—	Normalized	RT	602	309	26	Not given
								200	633	309	17	Not given
								400	587	216	25	Not given
								500	432	Not given	28	Not given
0.40C Steel	BS 080M40 (En8)	0.40	0.80	—	—	—	Normalized	RT	602	340	29	53
								250	633	293	19	41
								450	479	Not given	31	59

2. *Low alloy weldable steels*

½ Mo Steel	Similar to DIN 15Mo3	0.17	0.60	—	—	Mo	0.60	Normalized	RT	510	317	33	69
									400	510	232	30	73
									500	417	224	29	77
									600	293	185	34	77
½MoV Steel	—	0.12	0.60	—	—	Mo	0.50	Normalized	RT	587	394	23	76
						V	0.30	and	200	556	386	22	73
								tempered	400	479	340	25	77
									600	278	232	32	81
1CrMo Steel	BS 1501–620	0.15	0.70	—	0.95	Mo	0.50	Normalized	RT	479	286	21	68
								and	400	595	263	23	57
								tempered	500	525	232	24	65
									600	340	216	27	82
2¼CrMo Steel	BS 1501–622	0.13	0.60	—	2.20	Mo	1.10	Normalized	RT	641	417	18	75
								and	535	479	402	28	79
								tempered	610	309	263	47	89
3. *Low alloy direct hardening steels*													
¾MoV Steel	—	0.18	0.50	—	—	Mo	0.70	Hardened	RT	896	811	20	68
						V	0.20	and	400	741	680	21	62
								tempered	600	494	456	24	73
1CrMo Steel	—	0.40	0.40	—	1.10	Mo	0.70	Hardened	RT	1004	903	19	38
								and	300	942	857	Not given	Not given
								tempered	400	842	741	20	44
									600	479	324	28	64
3CrMo Steel	BS 722M24 (En40B)	0.24	0.60	—	3.30	Mo	0.55	Hardened	RT	757	556	20	Not given
								and	400	664	510	21	Not given
								tempered	450	618	479	25	Not given
									500	556	463	27	Not given

Table 22.48 TYPICAL HOT TENSILE PROPERTIES OF FORCED OR ROLLED STEELS IN THE LONGITUDINAL DIRECTION—*continued*

		Typical composition %						*Tensile properties*				
Material	*British or other standards*	C	Mn	Ni	Cr	*Other elements*	*Condition*	*Temperature* °C	*UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*RA* %
3CrMoV Steel	—	0.28	0.40	—	3.30	Mo 0.50 V 0.20	Hardened and tempered	RT 400 600	788 664 510	649 510 386	21 20 24	63 76 76
3CrVMoW Steel	—	0.23	0.30	—	2.70	V 0.70 Mo 0.50 W 0.50	Hardened and tempered	RT 200 400 600 700	988 896 811 571 355	903 826 764 510 301	17 18 16 16 21	40 38 36 33 36
3½Ni Steel	BS (En22)	0.34	0.60	3.50	—	—	Hardened and tempered	RT 200 400 500	788 741 726 448	571 525 510 340	21 23 22 24	Not given Not given Not given Not given
3½ NiCr Steel	—	0.30	0.50	3.50	0.60	—	Hardened and tempered	RT 200 400 500	896 849 849 695	757 710 726 602	20 17 16 19	Not given Not given Not given Not given
2½NiCrMo Steel	BS 826M31 (En25)	0.31	0.55	2.70	0.60	Mo 0.55	Hardened and tempered	RT 200 400 500	988 942 911 741	880 834 834 664	21 17 17 19	Not given Not given Not given Not given
4NiCrMo Steel	—	0.30	0.30	4.10	2.00	Mo 0.30	Hardened and tempered	RT 400 600	927 757 355	664 571 170	20 19 40	61 61 88
3NiCrMoV Steel	—	0.29	0.40	3.10	0.70	Mo 0.50 V 0.20	Hardened and tempered	RT 400 600	788 633 386	649 494 232	20 19 27	60 64 84

4NiCrMoV Steel	—	0.36	0.60	3.90	2.20	Mo V	0.50 0.20	Hardened and tempered	RT 400 550	927 772 525	695 587 293	17 17 28	56 55 77
4. *High alloy steels*													
8CrSi Valve steel	BS 401S45 (En52)	0.45	0.50	—	8.50	Si	3.50	Hardened and tempered	RT 400 600	942 726 270	718 471 178	23 24 52	53 60 93
13Cr Steel	BS 410S21 (En56A)	0.12	0.50	—	13.00	—		Hardened and tempered	RT 200 400 600	610 502 463 309	417 363 332 178	29 28 24 43	72 76 74 90
13Cr Steel	BS 420S37 (En56C)	0.24	0.50	—	13.0	—		Hardened and tempered	RT 200 400 600	703 595 541 293	541 456 432 293	23 23 18 38	60 62 58 80
13Cr Steel	DIN X40Cr13	0.40	0.50	—	12.0	—		Hardened and tempered	RT 400 600	772 687 347	541 Not given Not given	17 14 26	Not given 49 67
11CrVMoNb Steel	—	0.20	0.40	—	11.0	V Mo Nb	0.70 0.50 0.20	Hardened and tempered	RT 400 600 650	958 795 525 448	849 741 479 378	15 10 21 23	Not given Not given Not given Not given
11CrNiMoNbV Steel	—	0.20	0.80	1.20	10.5	Mo Nb V	0.70 0.60 0.20	Hardened and tempered	RT 400 600 700	1081 803 587 363	942 741 541 324	16 16 28 30	46 48 73 81
20Cr Steel	BS 442S19	0.06	0.80	—	21.0	—		Softened	RT 400 600	541 432 216	409 317 208	30 21 45	60 58 79
14/8CrNiMoAl Steel	Similar to USA PH-13/8Mo	0.03	0.80	8.50	14.5	Mo A	2.30 1.10	Precipitation hardened	RT 31.5 535	1683 1375 896	1591 1236 726	6 4 16	Not given Not given Not given

Table 22.48 TYPICAL HOT TENSILE PROPERTIES OF FORCED OR ROLLED STEELS IN THE LONGITUDINAL DIRECTION—*continued*

Material	British or other standards	Typical composition % C	Mn	Ni	Cr	Other elements		Condition	Tensile properties Temperature °C	UTS MPa	Yield stress MPa	Elong. (gl $5.65\sqrt{S_0}$) %	RA %
18/8CrNi Steel	BS 304S15 (En58E)	0.06	0.80	10.00	18.0	—		Softened	RT	571	216	52	70
									600	324	93	35	57
18/8CrNiTi Steel	BS 321S20 (En58B)	0.10	0.80	8.50	18.0	Ti	0.60	Softened	RT	656	255	46	68
									400	463	193	36	65
									600	378	162	31	67
18/11CrNiNb Steel	Similar to BS 347S17 (En58G)	0.08	1.50	11.0	17.5	Nb	1.20	Softened	RT	633	263	50	65
									400	432	178	33	64
									600	378	162	35	62
									750	239	Not given	42	73
17/13CrNiMo Steel	BS 316S16 (En58J)	0.07	1.40	12.50	16.50	Mo	2.80	Softened	RT	710	247	51	76
									600	463	124	43	62
									800	216	108	47	62
14/14CrNiW Valve steel	BS 331S40 (En54)	0.42	0.70	14.00	14.00	W	2.50	Softened	RT	973	556	22	24
						Si	1.50		400	656	456	20	33
									600	525	301	24	55
									800	263	139	35	74
20/8CrNiW Valve steel	BS (En55)	0.30	0.80	7.50	20.00	W	4.00	Softened	RT	834	463	33	36
						Si	1.30		400	656	371	26	43
									600	510	263	30	41
									800	247	Not given	43	55
23/12CrNiW Valve steel	BS (En55)	0.20	0.40	11.50	23.00	W	3.00	Softened	RT	718	402	28	34
						Si	1.60		400	610	301	30	42
									600	456	247	29	36
									800	232	Not given	41	41
25/12CrNi Steel	—	0.10	1.50	12.00	25.00	—		Softened	RT	656	340	40	70
									400	556	293	37	58
									600	432	239	30	55
									800	170	139	Not given	Not given

24/20CrNi Steel	BS 310S24	0.14	0.80	21.00	24.00	Si	1.00	Softened	RT	649	317	43	63
									400	556	201	37	63
									600	463	193	28	42
									800	193	Not given	40	42
18/18/7 CrNiCoMo-CuTi Steel	—	0.21	0.80	17.50	17.00	Co	7.00	Precipitation hardened	RT	687	409	32	43
						Mo	2.50		400	579	355	28	41
						Cu	2.50		600	510	355	22	29
						Ti	0.70		800	332	293	20	29
20/20/20 CrNiCoMo-WNb Steel	AICMA FE-PA91-HT	0.12	1.50	20.00	21.00	Co	20.00	Precipitation hardened	RT	811	394	35	48
						Mo	3.00		400	734	386	30	47
						W	2.00		600	602	324	29	45
						Nb	1.00		800	340	208	29	42
35/15NiCr Steel	—	0.10	1.00	35.00	15.00	—		Softened	RT	571	293	41	70
									400	463	224	28	42
									600	355	170	22	27
									800	170	139	16	20

Table 22.49 TYPICAL FATIGUE STRENGTH OF STEELS ON SMOOTH SPECIMENS AT ROOM AND HIGHER TEMPERATURES

Material	British or other standards	Typical composition %					Condition	Fatigue limit for 10^7 cycles of stress at temperatures indicated, MPa								Remarks
		C	Mn	Ni	Cr	Other elements		RT	100°C	200°C	300°C	400°C	500°C	600°C	650°C	
1. *Forged or rolled steels tested in longitudinal direction* *Carbon steels with up to 1.5% Mn content*																
Armco Iron	—	0.02	0.03	—	—	—	As rolled	±185	±170	±178	±232	±178	±116	—	—	—
0.20C Steel	BS070 M20 (En3)	0.20	0.70	—	—	—	Normalized	±193	±193	±193	±247	±232	±154	—	—	—
0.25C Steel	BS070 M26 (En4)	0.26	0.70	—	—	—	Normalized	±201	±193	±193	±247	±263	±185	—	—	—
0.30C Steel	BS080 M30 (En5)	0.30	0.80	—	—	—	Normalized	±232	—	—	—	—	—	—	—	—
0.40C Steel	BS080 M40 (En8)	0.40	0.80	—	—	—	Hardened and tempered	±278	—	—	—	—	—	—	—	—
0.55C Steel	BS070 M55 (En9)	0.55	0.65	—	—	—	Hardened and tempered	±293	—	—	—	—	—	—	—	—
CMn Steel	BS150 M19 (En14A)	0.28	1.50	—	—	—	Normalized	±278	—	—	—	—	—	—	—	—
Low alloy weldable steel																
½Mo Steel	—	0.14	0.43	—	—	Mo 0.50	Normalized	±317	—	—	±402	±371	±278	—	—	—
Low alloy direct hardening steel																
2NiCrMo Steel	—	0.27	Not given	2.0	0.90	Mo 0.40	Hardened and tempered	±432	±432	±432	±440	±432	±247	—	—	—
2¾CrMoVW Steel	—	0.23	0.30	—	2.70	Mo 0.50 V 0.70 W 0.50	Hardened and tempered	±440	—	—	—	—	±324	±247	—	4×10^7 cycles

3½Ni Steel	BS(En22)	0.40	0.80	3.50	—		Hardened and tempered	±525	±533	±556	±556	±517	±394	—	—	Rotating bending
3CrMo Steel	BS722M24 (En40B)	0.24	0.60	—	3.30	Mo 0.55	Hardened and tempered	±293	—	—	—	—	—	—	—	—
3NiCr Steel	BS653M31 (En23)	0.31	0.60	3.0	0.90		Hardened and tempered	±432	—	—	—	—	—	—	—	—
3NiCrMoV Steel	Similar to BS976M33	0.29	0.40	3.1	0.70	Mo 0.50 V 0.20	Hardened and tempered	±486	—	—	—	—	—	—	—	—
4NiCrMo Steel	Similar to BS835M30 (En30B)	0.30	0.50	3.9	1.20	Mo 0.35	Hardened and tempered	±525	±432	—	—	—	—	—	—	—
4½NiCrMo Steel	—	0.20	0.57	4.65	1.40	Mo 0.58	Hardened and tempered	±571	±448	—	—	—	—	—	—	—
High alloy steels																
13Cr Steel	BS410S21 (En56A)	0.12	0.50	—	13.0	—	Hardened and tempered	±340	—	—	—	—	—	—	—	—
13Cr Steel	BS420S37 (En56C)	0.24	0.50	—	13.0	—	Hardened and tempered	±402	±394	±386	±355	±309	±201	—	—	—
17CrNi Steel	BS431S29 (En57)	0.16	0.50	2.50	16.50	—	Hardened and tempered	±371	—	—	—	—	—	—	—	—
18/10CrNi Steel	BS304S15 (En58E)	0.06	0.80	10.0	18.0	—	Softened	±263	—	—	—	—	—	—	—	—
18/9CrNi Steel	BS302S17	0.07	1.50	9.5	18.0	—	Softened	±278	—	—	—	±216	±216	—	±208	—
18/10CrNi Steel	BS302S25 (En58A)	0.12	1.50	9.7	18.5	—	Softened	±293	—	—	—	±255	±263	—	±216	—
18/8CrNiTi Steel	BS321S20 (En58B)	0.10	0.80	8.5	18.0	Ti 0.60	Softened	±270	—	—	—	—	—	—	—	—

Table 22.49 TYPICAL FATIGUE STRENGTH OF STEELS ON SMOOTH SPECIMENS AT ROOM AND HIGHER TEMPERATURES—*continued*

Material	*British or other standards*	*Typical composition %* C	Mn	Ni	Cr	*Other elements*	*Condition*	*Fatigue limit for* 10^7 cycles *of stress at temperatures indicated,* MPa RT	100°C	200°C	300°C	400°C	500°C	600°C	650°C	*Remarks*
18/10CrNi-Nb Steel	Similar to BS347S17 (En58G)	0.08	1.50	11.0	17.5	Nb 1.20	Softened	±301	—	—	—	—	—	±208	±178	—
18/9CrNiMo Steel	BS315S16 (En58H)	0.07	1.00	9.5	18.0	Mo 1.25	Softened	±270	—	—	—	—	—	—	—	—
18/8CrNiMo Steel	—	0.07	0.50	8.0	18.0	Mo 2.70	Softened	±270	—	—	—	—	—	—	—	—
18/18CrNi-MoCuTi Steel	—	0.07	0.80	18.0	18.0	Mo 3.70 Cu 2.40 Ti 0.60	Precipitation hardened	±263	—	—	—	—	—	—	—	—
2. *Steel castings*																
Carbon steel castings	BS592 Grade B	0.32	0.77	—	—	—	Annealed	±229	—	—	—	—	—	—	—	—
							Normalized and tempered	±258								
1½Mn Steel Castings	BS1456 Grade B1	0.31	1.60	—	—	—	Normalized and tempered	±334	—	—	—	—	—	—	—	—
	BS1456 Grade B2	0.31	1.60	—	—	—	Hardened and tempered	±403	—	—	—	—	—	—	—	—
½NiCrMo Steel castings	BS1458 Grade A	0.36	0.89	0.38	0.59	Mo 0.32	Hardened and tempered	±372	—	—	—	—	—	—	—	—
1¾NiCrMo Steel castings	BS1458 Grade C	0.34	0.60	1.74	0.70	Mo 0.30	Hardened and tempered	±534	—	—	—	—	—	—	—	—

Table 22.50 TYPICAL HOT CREEP AND RUPTURE PROPERTIES OF FORGED OR ROLLED STEELS (BS 1501:Part 2:1970, DIN 17175:1959, 17240:1959, Stahl-Eisen Werkstoffblatt 550–57, 670–69)

Material	*British or other standards*	*Typical composition %* C	Mn	Ni	Cr	*Other elements*	*Condition*	*Stress to produce 1.0% strain* *Temperature* °C	MPa in 10 000 h	MPa in 100 000 h	*Stress to cause rupture* MPa in 10 000 h	MPa in 100 000 h
1. *Carbon steels*												
0.15C Steel	BS 040A12 DIN St35.8	0.13	0.50	—	—	—	Normalized	400	136	96	192	133
								450	80	49	113	68
								500	39	20	54	29
0.20C Steel	BS 070M20 DIN St45.8	0.20	0.70	—	—	—	Normalized	400	136	96	192	133
								450	80	49	113	68
								500	39	20	54	29
0.35C Steel	BS 080M36 DIN Ck35	0.36	0.80	—	—	—	Hardened and tempered	400	147	99	193	137
								450	80	49	113	68
								500	39	22	54	34
0.45C Steel	BS 080M46 DIN Ck45	0.46	0.80	—	—	—	Hardened and tempered	400	147	99	193	137
								450	80	49	113	68
								500	39	22	54	34
2. *Low alloy weldable steels*												
½Mo Steel	DIN 15Mo3	0.16	0.65	—	—	Mo 0.30	Normalized	450	216	167	304	246
								500	133	74	176	93
								530	85	37	105	48
1CrMo Steel	BS1501–620 DIN 13CrMo44	0.15	0.70	—	0.95	Mo 0.50	Normalized and tempered	450	247	193	371	286
								500	162	100	232	139
								560	63	31	93	40
1¼CrMo Steel	BS1501–621	0.12	0.55	—	1.25	Mo 0.55	Normalized and tempered	450	309*	224*	432	314
								500	181*	119*	258	168
								560	69*	31*	100	40
2¼CrMo Steel	BS1501-622 DIN 10CrMo910	0.13	0.60	—	2.20	Mo 1.10	Normalized and tempered	500	148	103	216	147
								550	83	53	116	77
								580	57	31	77	45

* Estimated

Table 22.50 TYPICAL HOT CREEP AND RUPTURE PROPERTIES OF FORGED OR ROLLED STEELS (BS 1501:Part 2:1970, DIN 17175:1959, 17240:1959, Stahl-Eisen Werkstoffblatt 550–57, 670–69)—*continued*

Material	*British or other standards*	*Typical composition %* C	Mn	Ni	Cr	*Other elements*	*Condition*	*Temperature* °C	*Stress to produce 1.0% strain* MPa in 10 000 h	MPa in 100 000 h	*Stress to cause rupture* MPa in 10 000 h	MPa in 100 000 h
1¼MnCrMoV Steel	BS1501-271	0.14	1.25	—	0.55	Mo 0.24 V 0.08	Normalized and tempered	450 500 550	263* 170* 74*	216* 100* 28*	371 235 102	309 139 39
1NiCrMoV Steel	BS1501-281	0.12	1.10	0.85	0.55	Mo 0.24 V 0.08	Normalized and tempered	450 500 550	216* 139* 62*	178* 85* 23*	297 187 82	247 111 31
1½NiCrMoV Steel	BS1501-282	0.15	1.10	1.50	0.50	Mo 0.35 V 0.10	Normalized and tempered	450 500 550	216* 139* 62*	178* 85* 23*	297 187 182	247 111 31
3. *Low alloy direct hardening steels*												
1CrMo Steel	DIN 24CrMo5	0.24	0.65	—	1.00	Mo 0.25	Hardened and tempered	450 500 550	227 139 62	171 93 25	310 176 79	225 117 37
1½CrMoV Steel	DIN 24CrMoV 55	0.24	0.45	—	1.35	Mo 0.55 V 0.20	Hardened and tempered	450 500 550	303 193 93	239 128 56	405 256 139	321 184 74
1½CrMoV Steel	DIN 21CrMoV 511	0.21	0.40	—	1.35	Mo 1.10 V 0.30	Hardened and tempered	450 500 550	340 230 120	276 165 65	423 303 156	349 212 93
2½CrMoV Steel	DIN 30CrMoV92	0.30	0.55	—	2.50	Mo 0.20 V 0.15	Hardened and tempered	450 500 550	246 158 74	187 99 36	324 216 99	264 137 46
4. *High alloy steels*												
9CrMo Steel	—	0.12	0.44	—	9.50	Mo 0.95	Hardened and tempered	590 650	43 19	14 6	59* 26	19* 8*

12CrMo Steel	DIN X19CrMo12 1	0.19	0.55	—	12.0	Mo 1.00	Hardened and tempered	500 550 600	241 137 59	187 93 34	300 176 83	235 117 46
12CrMoV Steel	DIN X22CrMoV12 1	0.22	0.55	—	12.00	Mo 1.00 V 0.30	Hardened and tempered	500 550 600	289 165 79	221 108 45	338 212 103	275 137 59
18/9CrNi Steel	BS304S15 (En58E)	0.06	0.80	10.00	18.0	—	Softened	600 650 700	85 57 39	46 29 17	116* 77* 54*	62* 39* 23*
16/13CrNiNb Steel	DIN X8CrNiNb 16 13	0.07	1.00	13.0	16.00	Nb 10 × C/1.2	Softened	600 650 700 750	113 79 49 34	79 49 26 15	158 103 63 45	108 63 34 20
17/13CrNiMo Steel	BS316S16 (En58J)	0.07	1.40	12.50	16.50	Mo 2.80	Softened	600 650 700 750	139 100 63 43	77 46 29 20	185* 131* 85* 56*	108* 62* 39* 26*
16/16 CrNiMoNb Steel	DIN X8CrNiMoNb 16 16	0.07	1.00	16.50	16.50	Mo 1.80 Nb 10 × C/1.2	Softened	600 650 700 750	158 108 63 42	108 63 34 15	225 137 83 54	151 83 45 20
16/16 CrNiWNb Steel	DIN X6CrNiWNb 16 16	0.06	1.00	16.50	16.50	W 3.00 Nb 10 × C/1.2 N 0.10	Softened	600 650 700 750	167 113 68 39	117 68 39 17	235 147 91 54	162 90 49 23
25/13CrNi Steel	—	0.06	1.55	13.40	24.9	—	Softened	650 700	69 48	39 17	93* 62*	54* 23*
24/20CrNi Steel	BS 310S24	0.14	0.80	21.00	24.0	Si 1.00	Softened	600 650 700	154 103 65	77 56 34	224* 139* 86	103* 74* 45*

*Estimated

Table 22.51 MECHANICAL PROPERTIES OF FORGED OR ROLLED STEELS AT SUBZERO TEMPERATURES IN THE LONGITUDINAL DIRECTION

Material	British or other standards	Typical composition % C	Mn	Ni	Cr	Other elements	Conditions	Temperature °C	Typical properties UTS MPa	Yield stress MPa	Elong. (g) $5.65\sqrt{S_0}$ %	RA %	Impact Test spec.	Impact J
1. *Carbon steels*														
Armco iron	—	0.02	0.03	—	—	—	Not given	RT	309	Not given	Not given	73	Izod	106
								−75	432	293	33	72	Izod	5.5
								−120	525	463	15	68	—	—
0.1C Steel	BS 040A10 (En2A)	0.10	0.45	—	—	—	As rolled	RT	463	340	27	72	Charpy	80
								−30	—	—	—	—	Charpy	60
								−45	—	—	—	—	Charpy	8
								−160	649	556	24	62	—	—
0.15C Steel	BS 040A12 (En2B)	0.13	0.50	—	—	—	Normalized	RT	463	355	28	67	Charpy	163*
								−65	—	—	—		Charpy	9.0*
								−160	710	571	30	58	—	—
0.20C Steel	BS 070M20 (En3)	0.20	0.70				Normalized	RT	430	215	21	65	Charpy	99*
								−20	—			—	Charpy	13.5*
								−80	—	—	—			2.7*
								−160	726	587	Not given	56		—
0.25C Steel	BS 070M26 (En4)	0.26	0.70	—	—	—	Normalized	RT	494	247	20	Not given	—	—
							Cold drawn	RT	571	432	11	Not given	Izod	27
								−40	757	Not given	11	Not given	Izod	3.4
0.35C Steel	BS 080M36	0.36	0.80	—	—	—	Normalized	RT	541	278	27	62	Charpy	110*
								−55	—		—	—	Charpy	30*
								−80	—			—	Charpy	11*
								−100	741	571	28	57		—
0.40C Steel	BS 080M40 (En8)	0.40	0.80	—	—	—	Hardened and tempered	RT	772	463	22	Not given	—	—
								−185	1112	Not given	9	Not given	—	—
0.45C Steel	BS 080M46	0.46	0.80	—	—	—	Normalized	RT	618	309	15	Not given	Charpy	22*
								80	896	Not given	14	Not given	Charpy	11*
							Hardened and tempered	RT	927	525	14	Not given	Charpy	68*
								−40	—	—	—	—	Charpy	36.5*
								−80	1050	Not given	12	Not given	Charpy	24.5*

0.50C Steel	BS 080M50 (En9) (En43A)	0.50	0.80	—	—		Normalized	RT	618	309	14	Not given	-	—
								−30	803	Not given	12	Not given		—
2. *Low alloy weldable steels*														
MnCrMoV Steel	BS 1501–271	0.14	1.40	—	0.70	Mo 0.28 V 0.10	Normalized and tempered	RT	649	463	18	Not given	Charpy V Izod	41 68
								0		—	—	—	Charpy V Izod	27 51.5
								−60	—	—	—	—	Izod	16
1NiCrMoV Steel	BS 1501–281	0.12	1.10	0.85	0.55	Mo 0.24 V 0.08 Nb 0.10	Normalized and tempered	RT	649	417	18	Not given		—
								−10	—	—	—	—	Charpy V	68
								−20	—	—	—	—	Charpy V	54
								−40		—	—	—	Charpy V	27
1½NiCrMoV Steel	BS 1501–282	0.15	1.10	1.50	0.50	Mo 0.35 V 0.10	Double normalized and tempered	RT	649	432	18	Not given		—
								−10	—	—	-	—	Charpy V	81
								−20	—	—		—	Charpy V	68
								−40		—	—	—	Charpy V	41
								50	—	—	—	—	Charpy V	27
3½Ni Steel	BS 1501–503	0.15	0.55	3.50	-	—	Normalized and tempered	RT	448	263	20	Not given	—	–
								−80	—	—	—	—	Charpy V	34
								−100	–	—	—	—	Charpy V	17.5
5Ni Steel	DIN 12Ni9	0.13	0.40	5.20	—	—	Hardened and tempered	RT	710	Not given	22	74	—	
								−150	1050	Not given	22	57	—	—
								−195	1205	Not given	18	50	—	-
3. *Low alloy direct hardening steels*														
1CrV Steel	—	0.29	0.70	—	1.00	V 0.20	Hardened and tempered	RT	896	Not given	13	Not given	—	—
								−75	1035	Not given	13	Not given	—	—
¾CrMo Steel	—	0.31	0.65	—	0.70	Mo 0.20	Hardened and tempered	RT	880	Not given	17	Not given	Izod	110
								−40	1035	Not given	17	Not given	Izod	109
1CrMo Steel	BS 709M40 (En19)	0.40	0.80	—	1.10	Mo 0.30	Hardened and tempered	RT	849	494	15	70	Charpy	141*
								−70	—	-	—	—	Charpy	84*
								−185	1251	1143	19	47	—	—

*Charpy specimen—Izod notch V = Charpy specimen- V notch.

Table 22.51 MECHANICAL PROPERTIES OF FORGED OR ROLLED STEELS AT SUBZERO TEMPERATURES IN THE LONGITUDINAL DIRECTION—*continued*

		Typical composition %							*Typical properties*					
													Impact	
Material	*British or other standards*	C	Mn	Ni	Cr	*Other elements*	*Conditions*	*Temperature* °C	*UTS* MPa	*Yield stress* MPa	*Elong.* (gl $5.65\sqrt{S_0}$) %	*RA* %	*Test spec.*	J
1¼NiCr Steel	BS 640M40 (En111)	0.40	0.80	1.30	0.65	—	Hardened and tempered	RT	1004	680	13	60	Izod	54
								−185	1699	Not given	4.5	48	—	—
1NiCrMo Steel	—	0.47	0.80	1.10	1.00	Mo 0.20	Hardened and tempered	RT	1081	Not given	12	Not given	—	—
								−76	1220	Not given	11	Not given	—	—
2½NiCrMo Steel	BS 826M31 (En25)	0.31	0.55	2.70	0.60	Mo 0.55	Hardened and tempered	RT	1004	741	13	65	Izod	34
								−60	1127	988	12	63	—	—
								−180	1390	1266	12	63	—	—
2½NiCrMo Steel	—	0.34	0.50	2.30	1.90	Mo 0.40	Hardened and tempered	RT	1158	1019	15	65	—	—
								−70	1251	1127	15	63	—	—
								−185	1560	1390	17	62	—	—
3½Ni Steel	BS (En21)	0.34	0.70	3.30	—	—	Hardened and tempered	RT	927	865	15	64	Charpy	109*
								−75	1066	988	14	60	Charpy	38*
3NiCr Steel	BS 653M31 (En23)	0.31	0.60	0.90	0.90	—	Hardened and tempered	RT	1004	757	12	60	Charpy	80
								−95	—	—	—	—	Charpy	61
								−185	1683	1668	5	49	—	—
4½NiCr Steel	BS (En30A)	0.30	0.50	4.40	1.40	—	Hardened and tempered	RT	865	Not given	24	Not given	—	—
								−30	1019	Not given	26	Not given	—	—
								−90	1050	Not given	23	Not given	—	—
4NiCrMo Steel	BS 835M30 (En30B)	0.30	0.50	3.90	1.20	Mo 0.35	Hardened and tempered	RT	1544	1235	17	54	Charpy	34*
								−80	1761	1266	17	58	—	—
								−100	—	—	—	—	Charpy	20.5*
								−196	2039	1544	17	50	—	—
4. *High alloy steels*														
9Ni Steel	BS 1501–509, 1503–509 DIN X8Ni9 ASTM A353	0.10	0.55	9.25	—	—	Hardened and tempered	RT	695	525	18	Not given	Charpy	76
								−100	—	—	—	—	Charpy V	68
								−160	—	—	—	—	Charpy V	47
								−196	1158	911	18	Not given	Charpy	64
													Charpy V	34

13Cr Steel	BS 420S45 (En56D)	0.32	0.40	—	13.5	—	Hardened and tempered	RT	927	587	13	37	—	—
								−185	1 792	1 452	3	4	—	—
17Cr Steel	BS 430S15 (En60	0.09	0.45	—	17.0	—	Softened	RT	432	278	25	71	Charpy	61*
								−20	—	—	—	—	Charpy	34*
								−60	—	—	—	—	Charpy	6.8*
								−185	1 004	849	12	14	—	—
20CrCu Steel	—	0.25	0.50	—	20.0	Cu 1.0	Softened	RT	633	355	21	59	—	—
								−185	680	618	Not given	Not given	—	—
17CrNi Steel	BS 431S29 (En57)	0.14	Not given	2.50	17.5	—	Hardened and tempered	RT	1 004	680	21	Not given	—	—
								−90	1 050	Not given	18	Not given	—	—
18/10CrNi Steel	BS 302S35 (En58A) DIN X12Cr-Ni 18.9	0.12	0.50	9.7	18.5	—	Softened	RT	510	216	47	74	Izod	155U
								−60	942	340	52	74	Izod	146U
								−120	1 236	494	43	63	Izod	146U
								−180	1 544	510	40	55	Izod	146U
18/8Cr NiMo Steel		0.05	0.50	8.20	18.0	Mo 2.70	Softened	RT	710	Not given	58	Not given	—	—
								−30	896	Not given	51	Not given	—	—
								−55	1 050	Not given	42	Not given	—	—
								−90	1 174	Not given	35	Not given	—	—
14/14CrNi Steel	BS (En58D)	0.11	Not given	14.0	14.2	—	Softened	RT	602	232	44	76	Izod	159U
								−65	772	293	51	76	Izod	160U
								−120	958	417	49	72	Izod	159U
								−180	1 328	819	45	60	Izod	157U
25/20CrNi Steel	BS 310S24	0.14	0.80	21.0	24.0	Si 1.00	Softened	RT	649	317	43	Not given	Charpy	203*
								−30	741	Not given	52	Not given	—	—
								−50	—	—	—	—	Charpy	190*
								−90	849	Not given	51	Not given	—	—
								−150	—	—	—	—	Charpy	122*
26Ni Steel	—	0.40	1.50	26.0	—	—	Softened	RT	695	371	33	52	—	—
								−185	1 421	1 097	10	10	—	—
36Ni Steel	—	0.16	0.90	36.0	—	—	Softened	RT	556	355	28	58	—	—
								−250	988	880	18	60	—	—

*Charpy specimen—Izod notch U = Unbroken V = Charpy specimen—V notch U = unbroken.

Table 22.52 TOOL STEELS AND THEIR USES
(BS 4659: 1989)

Material	*British or other standards*	*Chemical composition limits %* C	Si	Mn	Cr	Mo	W	V	Co	*Other elements*	*Typical uses*
1. *Carbon tool steels*											
0.8C Steel	DIN C80W1	0.75 0.85	0.10 0.25	0.10 0.25	— —	— —	— —	— —	— —	— —	Cold heading dies, chisels, mandrels, punches, rivet snaps, vice jaws, drifts
0.9C Steel	BS BW1A*	0.85 0.95	0.30 max	0.35 max	0.15 max	0.10 max	— —	— —	— —	Ni 0.20 max	Gauges, chisels, punches, shear blades
1C Steel	BS BW1B*	0.95 1.10	0.30 max	0.35 max	0.15 max	0.10 max	— —	— —	— —	Ni 0.20 max	Large drills, reamers, cutters, cold heading tools, shear blades, wood working tools, lathe centres
1.2C Steel	BS BW1C*	1.10 1.30	0.30 max	0.35 max	0.15 max	0.10 max	— —	— —	— —	Ni 0.20 max	Twist drills, cutters, reamers, taps, files, screw gauges, woodworking tools
1CV Steel	BS BW2	0.95 1.10	0.30 max	0.35 max	0.15 max	0.10 max	— —	0.15 0.35	— —	Ni 0.20 max	Large drills, reamers, cutters, cold heading tools, shear blades, woodworking tools, lathe centres, when fine grained shallow case is required with increased toughness
2. *Hot work tool steels*											
1¾ NiCr-MoV Steel	DIN 55Ni-CrMoV6 Similar to BS No5 die steel	0.55	0.30	0.60	0.70	0.30 (Typical)	—	0.10	—	Ni 1.70	Solid dies for drop-hammer or press forging
3CrMoV Steel	Bs BH10	0.30 0.40	0.75 1.10	0.40 max	2.80 3.20	2.65 2.95	— —	0.30 0.50	— —	— —	Mandrels, hot extrusion and forging dies, punches, die inserts, gripper and header dies, hot shears aluminium die casting dies
3CrMoV Co Steel	BS BH10A	0.30 0.40	0.75 1.10	0.40 max	2.80 3.20	2.65 2.95	— —	0.30 1.10	2.80 3.20	— —	Close die forging tools
5CrMoV Steel	BS BH11	0.32 0.42	0.85 1.15	0.40 max	4.75 5.25	1.25 1.75	— —	0.30 0.50	— —	— —	Die casting dies and die inserts for light alloys, punches, piercing tools, mandrels, forging dies and die inserts, ejector pins, hot extrusion dies, sleeves, slides
5CrMoV Steel	BS BH13	0.32 0.42	0.85 1.15	0.40 max	4.75 5.25	1.25 1.75	— —	0.90 1.10	— —	— —	As for BH11, when higher performance is required

*BS 4659: 1971; omitted from BS 4659: 1989 but still referred to.

Table 22.52 TOOL STEELS AND THEIR USES—*continued*
(BS 4659: 1989)

Material	*British or other standards*	*Chemical composition limits %* C	Si	Mn	Cr	Mo	W	V	Co	*Other elements*	*Typical uses*
5CrMo-WV Steel	BS BH12	0.30 0.40	0.85 1.15	0.40 max	4.75 5.25	1.25 1.75	1.25 1.75	0.50 max	— —	— —	Extrusion dies, gripper and header dies, forging die inserts, punches, mandrels, sleeves
4WCrV Steel	DIN X30-WCrV53	0.30	0.20	0.30	2.40	— (Typical)	4.30	0.60	—	—	Mandrels, hot extrusion and forging dies, punches, die inserts, gripper and header dies, hot shears, aluminium die casting dies
4WCrCo-VMo Steel	BS BH19	0.35 0.45	0.40 max	0.40 max	4.00 4.50	0.45 max	4.00 4.50	2.00 2.40	4.00 4.50	— —	Extrusion dies and die inserts, forging die inserts, punches and mandrels when the highest performance is required
9WCr-MoV Steel	BS BH21	0.25 0.35	0.40 max	0.40 max	2.25 3.25	0.60 max	8.50 10.00	0.40 max	— —	— —	Mandrels, hot blanking dies, hot punches, extrusion dies and die casting dies for brass, piercer points, gripper dies, hot headers–when high performance is required
9WCrMo VNi Steel	BS BH21A	0.20 0.30	0.40 max	0.40 max	2.25 3.25	0.60 max	8.50 10.00	0.50 max	— —	Ni 2.0 2.5	Hot extrusion tools
18WCrMo VCo Steel	BS BH26*	0.50 0.60	0.40 max	0.40 max	3.75 4.50	0.60 max	17.50 18.50	1.00 1.50	0.60 max	— —	Closed die forging tools
3. *Plastic moulding steels*											
1½CrMo Steel	BS P20	0.28 0.40	0.4 0.6	0.65 0.95	1.5 1.8	0.35 0.55	— —	— —	— —	0.40 max	Dies for plastic moulding
4NiCrMo Steel	BS P30	0.26 0.34	0.4 max	0.45 0.70	1.1 1.4	0.20 0.35	— —	— —	— —	3.1 4.3	Dies for plastic moulding
4. *Shock resisting tool steels*											
2½WCrV Steel	BS BS1	0.48 0.55	0.70 1.00	0.30 0.70	1.20 1.70	— —	2.00 2.50	0.10 0.30	— —	— —	Bolt header dies, chipping and caulking chisels, concrete drills, forming dies, grippers, mandrels, punches, pneumatic tools, beading tools, scarfing tools, swaging dies, shear blades
1SiMoV Steel	BS BS2*	0.45 0.55	0.90 1.20	0.30 0.50	— —	0.30 0.60	— —	0.10 0.30	— —	— —	Hand and pneumatic chisels, forming tools, ejector pins, mandrels, shear blades, spindles, stamps, tool shanks

* BS 4659: 1971; omitted from BS 4659: 1989.

Table 22.52 TOOL STEELS AND THEIR USES—*continued*
(BS 4659: 1989)

Material	*British or other standards*	*Chemical composition limits %* C	Si	Mn	Cr	Mo	W	V	Co	*Other elements*	*Typical uses*
2SiCrV Steel	BS BS5*	0.50 0.60	1.60 2.10	0.60 0.80	— —	0.30 0.60	— —	0.10 0.30	— —	— —	Hand and pneumatic chisels, forming tools, ejector pins, mandrels, shear blades, spindles, stamps, tool shanks, lathe collets, bending dies, punches, rotary shears
5. *Hammer die steels*											
										Ni	
1.5NiCr-Mo Steel	BS 224 BS 225	0.49 0.57	0.35 0.70	0.70 1.0	0.70 1.10	0.40 1.25	— —	— —	— —	1.25 1.80	Cold stamping, hammer dies, forming tools, punches, etc.
6. *Cold work tool steels*											
										Ni	
12CrV Steel	BS BD3	1.90 2.30	0.60 max	0.60 max	12.0 13.0	— —	— —	0.50 max	— —	0.40 max	Blanking dies, cold forming dies, thread rolling dies, shear blades, slitter knives, forming rolls, seaming rolls, burnishing tools, punches, gauges, crimping dies, swaging dies
										Ni	
12CrMoV Steel	Bs BD2	1.40 1.50	0.60 max	0.60 max	11.50 12.50	0.70 1.20	— —	0.25 1.00	— —	0.40 max	Blanking dies, cold forming dies, drawing dies, thread rolling dies, shear blades, slitter knives, forming rolls, burnishing tools, punches, gauge, knurling tools, lathe centres, broaches, cold extrusion dies, mandrels, swaging dies
										Ni	
13CrMoV Steel	BS BD2A	1.60 1.90	0.60 max	0.60 max	12.00 13.00	0.70 0.90	— —	0.25 1.00	— —	0.40 max	Coining dies
										Ni	
5CrMoV Steel	BS BA2	0.95 1.05	0.40 max	0.30 0.70	4.75 5.25	0.90 1.10	— —	0.15 0.40	— —	0.40 max	Thread rolling dies, extrusion dies, trimming, blanking and coining dies, mandrels, shear blades, spinning rolls, forming rolls, gauges, beading dies, burnishing tools, embossing dies, plastic moulds, stamping dies, bushes, punches, liners for brick moulds
										Ni	
2MnMo-Cr Steel	BS BA6	0.65 0.75	0.40 max	1.80 2.10	0.85 1.15	1.20 1.60	— —	— —	— —	0.40 max	Blanking, forming, coining and trimming dies, punches, shear blades, spindles, mandrels, plastic moulds

Table 22.52 TOOL STEELS AND THEIR USES—*continued*
(BS 4659: 1989)

Material	*British or other standards*	*Chemical composition limits %* C	Si	Mn	Cr	Mo	W	V	Co	*Other elements*	*Typical uses*
1¼MnCr-WV Steel	BS BO1	0.85 1.00	0.40 max	1.10 1.35	0.40 0.60	— —	0.40 0.60	0.25 max	— —	Ni 0.40 max	Blanking, drawing and trimming dies, plastic moulds, paper slitters, shear blades, taps, reamers, gauges, jigs, bending and forming dies, bushes, punches
1¾MnV Steel	BS BO2	0.85 0.95	0.40 max	1.50 1.80	— —	— —	— —	0.25 max	— —	Ni 0.40 max	Blanking, stamping, trimming and forming dies and punches, threading dies, taps, reamers, gauges, plugs, jigs, broaches, circular cutters and saws, bushes
1½CrMn Steel	BS BL1	0.95 1.10	0.40 max	0.40 0.70	1.2 1.6	— —	— —	— —	— —	Ni 0.4 max	Ball bearings, taps, broaches, files, mandrels, cold rolls, gauges, drills
1½Cr-V Steel	BS BL3*	0.95 1.05	0.40 max	0.40 max	1.30 1.50	— —	— —	0.10 0.30	— —	— —	Mandrels, cold rolls, ball bearings, precision gauges, reamers, broaches, taps, drills, thread rolling dies, files
1½WCrV Steel	BS BF1*	1.15 1.35	0.40 max	0.40 max	0.25 0.50	— —	1.30 1.60	0.30 max	— —	— —	Taps, broaches, reamers, drills
3V Steel	DIN 145-V33	1.45	0.30	0.40	—	— (Typical)	—	3.30	—	—	Cold heading dies and punches
7. High speed tool steels											
3-3-2 WMoV Steel	DIN S3.3.2	0.95 1.03	0.40 max	0.40 max	3.80 4.50	2.50 2.80	2.70 3.00	2.20 2.50	— —	— —	Hacksaw and circular saw blades for metal cutting
2.9.1 WMoV Steel	BS BM1	0.75 0.85	0.40 max	0.40 max	3.75 4.50	8.00 9.00	1.00 2.00	1.00 1.25	1.00 max	— —	Drills, taps, reamers, milling cutters, hobs, punches, lathe and planer tools, form cutters, saws, chasers, broaches, routers, woodworking tools
2-9-2 WMoV Co Steel	BS BM34*	0.85 0.95	0.40 max	0.40 max	3.75 4.50	8.00 9.00	1.70 2.20	1.75 2.05	7.75 8.75	— —	Cutting tools
6.5.2 WMoV Steel	BS BM2	0.82 0.92	0.40 max	0.40 max	3.75 4.50	4.75 5.50	6.00 6.75	1.75 2.05	1.20 max	— —	Drills, taps, reamers, milling cutters, hobs, form cutters, saws, lathe and planer tools, chasers, broaches, boring tools, cold forming tools, e.g. punches for cold extrusion, cold heading die inserts

* BS 4659: 1971; omitted from BS 4659: 1989.

Table 22.52 TOOL STEELS AND THEIR USES—*continued*
(BS 4659: 1989)

Material	*British or other standards*	*Chemical composition limits %* C	Si	Mn	Cr	Mo	W	V	Co	*Other elements*	*Typical uses*
6.5.2Co WMoVCo Steel	BS M35	0.85 0.95	0.40 max	0.40 max	3.75 4.50	4.75 5.25	6.00 6.75	1.75 2.15	4.6 5.2	— —	As for BM2, esp. cutting tools
6-5-4 WMoV Steel	BS BM4	1.25 1.40	0.40 max	0.40 max	3.75 4.50	4.25 5.00	5.75 6.50	3.75 4.25	1.00 max	— —	Heavy duty broaches, reamers, milling cutters, chasers, form cutters, lathe and planer tools, blanking dies and punches, swaging dies
6.5.4 WMoV Co Steel	BS BM15	1.45 1.60	0.40 max	0.40 max	4.50 5.00	2.75 3.25	6.25 7.00	4.75 5.25	4.5 5.5	— —	Cutting tools
6.5.2.5 WMo-VCo Steel	DIN S6-5-2-5	0.88 0.96	0.40 max	0.40 max	3.80 4.50	4.70 5.20	6.00 6.70	1.70 2.00	4.50 5.00	— —	Milling cutters, twist drills and taps, particularly suitable for intermittent cutting and drilling
2-9-1-8 WMo VCo Steel	BS BM42	1.00 1.10	0.40 max	0.40 max	3.50 4.25	9.00 10.00	1.00 2.00	1.00 1.30	7.50 8.50	— —	Heavy duty drills, reamers, form cutters, lathe tools, hobs, broaches, milling cutters, twist drills
18-0-1 W Steel	BS BT1	0.70 0.80	0.40 max	0.40 max	3.75 4.50	0.70 max	17.5 18.5	1.00 1.25	1.00 max	— —	Drills, taps, reamers, hobs, lathe and planer tools, broaches, burnishing dies, chasers, form cutters, milling cutters
18-0-2 W Steel	BS BT2*	0.75 0.85	0.40 max	0.40 max	3.75 4.50	0.70 max	17.50 18.50	1.75 2.05	0.60 max	— —	Cutting tools
18-1-1-5 WMo-VCo Steel	BS BT4	0.70 0.80	0.40 max	0.40 max	3.75 4.50	1.00 max	17.5 18.5	1.00 1.25	4.50 5.50	— —	As for BT1, when higher performance is required
19-1-2-10 WMoV Co Steel	BS BT5	0.75 0.80	0.40 max	0.40 max	3.75 4.50	1.00 max	18.50 19.50	1.75 2.05	9.00 10.00	— —	Cutting tools
20-1-2-12 WMo-VCo Steel	BS BT6	0.75 0.85	0.40 max	0.40 max	3.75 4.50	1.00 max	20.0 21.0	1.25 1.75	11.25 12.25	— —	Heavy duty lathes and planer tools, drills, cut-off tools, milling cutters, hobs
12-1-5-5 WMo-VCo Steel	BS BT15	1.40 1.60	0.40 max	0.40 max	4.25 5.00	1.00 max	12.0 13.0	4.75 5.25	4.50 5.50	— —	Heavy duty form cutters, milling cutters, broaches, blanking dies, lathe and planer tools
14-1 WV Steel	BS BT21	0.60 0.70	0.40 max	0.40 max	3.50 4.25	0.70 max	13.50 14.50	0.40 0.60	1.00 max	— —	Cutting tools
22.1 WV Steel	BS BT20*	0.75 0.85	0.40 max	0.40 max	4.25 5.00	1.00 max	21.00 22.50	1.40 1.60	0.60 max	— —	Cutting tools
9-3-3-9 WMo-VCo Steel	BS BT42	1.25 1.40	0.40 max	0.40 max	3.75 4.50	2.75 3.50	8.50 9.50	2.75 3.25	9.00 10.00	— —	Heavy duty milling cutters and form cutters when high performance is required

* BS 4569: 1971, omitted from BS 4569: 1989.

Table 22.53 TOOL STEEL HEAT TREATMENTS AND HARDNESS (BS 4659: 1989)

		Annealing	*Hardening*		*Tempering*	*Hardness*		
Material	*British or other standard*	°C	°C	*Quenching medium*	°C	*Annealed* Max HB	*Heat treated* Min HV	*Remarks*
1. *Carbon tool steels*								
0.8C Steel	DIN C80W1	680/710	780/810	Water or brine	150/350	207	790	
0.9C Steel	BS BW1A*	740/770	770/790	Water or brine	150/350	207	790	The wear resistance increases but the toughness decreases with increasing carbon content
1C Steel	BS BW1B*	740/770	770/790	Water or brine	150/350	207	790	
1.2C Steel	BS BW1C*	740/770	760/780	Water or brine	150/350	207	790	
1CV Steel	BS BW2	740/7	780/800	Water or brine	180/350	207	790	The V addition reduces the case depth, and raises the resistance to cracking
2. *Hot work tool steel*								
1¾NiCr-MoV Steel	DIN 55NiCr MoV6 Similar to Bs No. 5 Die Steel	650/700	830/870	Oil	500/600	—	—	Tough and wear resistant
3CrMoV Steel	BS BH10	850/870	1 000/1 060[a]	Oil or air	530/650	229	—	Wear resistance and fairly tough. Resistant to softening on tempering
3CrMoV Co Steel	BS BH10A	850/870	1 000/1 060[a]	Air or oil	530/650	241	—	Wear resistant
5CrMoV Steel	BS BH11	850/870	1 000/1 030[a]	Air or oil	530/650	229	—	Wear resistant and tough
5CrMoV Steel	BS BH13	850/870	1 020/1 030[a]	Air or oil	530/650	229	—	More resistant to wear and softening on tempering than BH11
5CrMo-WV Steel	BS BH12	850/870	1 000/1 030[a]	Air or oil	530/650	229	—	Wear resistant and tough
4WCrV Steel	X30WCrV53	750/800	1 060/1 100[a]	Oil, air or salt bath of 500/550°C temperature	530/650	—	—	Less tough but more resistant to softening on tempering than BH11. Not suitable for water cooling in service
4WCrCo-VMo Steel	BS BH19	850/870	1 150/1 200[a]	Air or oil	530/650	248	—	Higály resistant to wear and softening on tempering. Not suitable for water cooling in service
9Wcr-MoV Steel	BS BH21	870/890	1 100/1 180[a]	Oil or air	560/675	235	—	Very resistant to softening on tempering. Not suitable for water cooling in service

* BS 4659: 1971, omitted from BS 4659: 1989.
[a] Pre-heat 800°C.

Table 22.53 TOOL STEEL HEAT TREATMENTS AND HARDNESS—*continued*
(BS 4659: 1989)

		Annealing	*Hardening*		*Tempering*	*Hardness*		
Material	*British or other standard*	°C	°C	*Quenching medium*	°C	*Annealed* Max HB	*Heat treated* Min HV	*Remarks*
9WCrMo V Steel	BS BH21A	870/890	1 100/1 170◊	Oil or air	560/675	235	—	Resistant to softening
18WCrMo V Steel	BS BH26*	870/890	1 180/1 260	Oil or air	550/570	—	—	Resistant to softening
3. *Plastic moulding steels*								
1½CrMo Steel	BS P20	—	850/880	Oil	180/650	—	—	Varies
4NiCrMo Steel	BS P30	640/660	810/830	Air or oil	180/650	—	—	Varies
4. *Shock resisting tool steels*								
2¼WCrV Steel	BS BS1	790/820	870/820	Oil	200/650	229	600	Tough and wear resistant
1SiMoV Steel	BS BS2*	790/820	850/900	Water or oil	175/425	—	—	Tough and wear resistant
2SiMoV Steel	BS BS5*	790/820	870/920	Oil	175/425	—	—	More resistant to wear, but less tough, than BS2
5. *Hammer die steels*								
1½NiCrMo Steel	BS 224 225	850/870†	820/840	Oil or water	520/660	—	A†444/7 A 401/29 B 363/88 C 331/52 D 302/321 E 269/93	
6. *Cold work tool steels*								
12CrV Steel	BS BD3	850/870	950/1 000◊	Air or oil	150/220 450/550	255	763	Highly resistant to wear and abrasion. Resistant to corrosion and softening on tempering. Very little distortion after air hardening. Low temper for hardness; high temper for toughness
12CrMoV Steel	BS BD2	850/870	980/1 030◊	Air or oil	150/220 450/550	255	735	Similar to, but tougher than, BD3
13CrMoV Steel	BS BD2A	850/870	980/1 030◊	Oil or air	150/220 450/550	255	763	Tough and wear resistant
5CrMoV Steel	BS BA2	850/870	950/980◊	Air	150/550	241	735	Tougher, but less corrosion and wear resistant than BD2. Very little distortion after hardening

**Double tempering.
† Treble tempering.
* BS 4659: 1971, omitted from BS 4659: 1989.
◊ Pre-heat 800°C.

Table 22.53 TOOL STEEL HEAT TREATMENTS AND HARDNESS—*continued*
(BS 4659: 1989)

Material	*British or other standard*	*Annealing* °C	*Hardening* °C	*Quenching medium*	*Tempering* °C	*Hardness* *Annealed* Max HB	*Heat treated* Min HV	*Remarks*
2MnMo-Cr Steel	BS BA6	730/750	830/850[+]	Air	150/250	241	735	Less resistant to wear and softening on tempering than BD2. Very little distortion after hardening
1½MnCr-WV Steel	BS BO1	760/780	780/820	Oil	150/300	229	735	Hard and wear resistant. Little distortion after hardening
1¾MnV Steel	BS BO2	760/780	760/780	Oil	150/300	229	735	Hard and wear resistant. Little distortion after hardening
1½CrV Steel	BS BL3*	790/810	820/840 790/810	Oil Water	175/320	—	760 min	Hard and wear resistant
1½WCrV Steel	BS BF1*	780/800	780/800	Oil or water	175/250	—	760 min	Hard and wear resistant
3V Steel	DIN 145V33	720/760	800/920	Water	100/250	—	—	Very hard and wear resistant. The case depth is controlled by the hardening temperature
1½CrMn Steel	BS BL1	780/820	800/850	Oil or water	150/300	—	—	
7. *High speed steels*								
3.3.2 WMoV Steel	DIN S3.3.2	800/840	1 180/1 220[◆]	Oil, air or salt bath at 500°C	520/550*	—	—	Steel for special applications, e.g. metal cutting saws
2-8-1 WMov Steel	BS BM1	850/870	1 190/1210[◆]	Oil, air or salt bath at 500/560°C	530/550**	241	823	General purpose cutting tools
2-9-2 WMoV Steel	BS BM34*	870/900	1 215/1 235[◆]	Oil, air or salt bath at 500/560°C	530/550**	—	—	General purpose cutting tools
6.5.2 WMoV Steel	BS BM2	850/870	1 210/1 230[◆]	Oil, air or salt bath At 500/560°C	550/570**	248	836	General purpose cutting tools
6.5.2Co WMoVCo Steel	BS BM35	870/890	1 215/1235[◆]	Oil, air or salt bath at 500/560°C	530/550†	269	869	
6.5.4 WMoV Steel	BS BM4	850/870	1 200/1 220	Oil, air or salt bath At 500/560°C	540/560**	255	849	Steel for special applications when very high resistance to wear is required

** Double tempering.
* BS 4659: 1971, omitted from BS 4659: 1989.
◆ Pre-heat 800°C.

Table 22.53 TOOL STEEL HEAT TREATMENTS AND HARDNESS—*continued*
(BS 4659: 1989)

		Annealing	*Hardening*		*Tempering*	*Hardness*		
Material	*British or other standard*	°C	°C	*Quenching medium*	°C	*Annealed* Max HB	*Heat treated* Min HV	*Remarks*
6.5.4 WMoV Co Steel	BS BM15	870/900	1 210/1 230◆	Oil, air or salt bath at 500/560°C	540/560†	277	869	High wear resistance
6.5.2.5 WMo-VCo Steel	DIN S6-5.2.5	800/840	1 210/1 240◆	Oil, air or salt bath at 500/560°C	540/570†	—	—	Steel of high hot hardness, particularly suitable for intermittent cutting and drilling
2-9-1-8 WMo-VCo Steel	BSμBM42	870/900	1 180/1 200◆	Oil, air or salt bath at 500/560°C	520/540†	269	897	Steel for special applications when very high hardness is required
18-0-1 WV Steel	BS BT1	870/890	1 270/1 290◆	Oil, air or salt bath at 500/560°C	550/570**	255	823	General purpose cutting tools
18-0-2 WV Steel	BS BT2*	870/890	1 270/1 290◆	Oil, air or salt bath at 500/560°C	550/570**	–	—	General purpose cutting tools
18-1-1-5 WMo-VCo Steel	BS BT4	880/900	1 280/1 300◆	Oil, air or salt bath at 500/560°C	550/570†	277	849	Steel of high hot hardness, is used at higher speed for heavier cuts than is BT1
19.1.2.10 MoWVCo Steel	BS BT5	880/900	1 290/1 310◆	Oil, air or salt bath at 500/560°C	550/570†	290	869	
20.1.2.12 WMo-VCo Steel	BS BT6	880/900	1 290/1 310	Oil, air or salt bath at 500/560°C	550/570†	302	869	Steel for special applications when the highest hot hardness is required
12-1-5-5 WMo-VCo Steel	BS BT15	870/890	1 230/1 250◆	Oil, air or salt bath at 500/560°C	550/570†	290	890	Steel for special applications when the highest wear resistance is required
14-1 WV Steel	BS BT21	850/870	1 270/1 290◆	Oil, air or salt bath at 500/560°C	550/570	255	798	Steel for less arduous service
9-3-3-9 WMo-VCo Steel	BS BT42	850/870	1 200/1 240◆	Oil, air or salt bath at 500/560°C	550/570†	277	912	Steel for special applications when both the highest wear resistance and highest hot hardness are required

* BS4659: 1971, omitted from BS4659: 1989.
† Treble tempering.
** Double tempering.
◆ Pre-heat 800°C.

2.11 Other metals of industrial importance

In Table 22.54 are summarized the mechanical properties of metals of industrial importance not included in previous tables. Unless otherwise indicated, the data refer, as far as possible, to the purest metals available.

Table 22.54 MECHANICAL PROPERTIES OF OTHER METALS OF INDUSTRIAL IMPORTANCE

Metal	*Condition*	*Purity* %	*Heat treatment*	*Proof stress* MPa	*UTS* MPa	*Elong.* %	*Hardness* HV	*Impact strength* J	*Refs.*[1]
Ag	Soft	99.9	Annealed 600°C	—	172	50	25	5	1
	Hard	99.9	Cold worked, 70% reduction	—	330	4	95	—	1
Ag–Cu (Sterling silver)	Soft	Ag > 92.5	Annealed 550°C	—	255	37	—	—	—
	Hard	Cu 7.5	Cold drawn 50%	—	430	5	—	—	—
Au	Soft	99.99	Annealed 450°C	—	130	40–50	20–30	—	2
	Hard	99.9	60% reduction	205	220	4	60	—	3, 4
Be	Soft	99.5	Hot pressed	240	310	2	(150)	1[2]	5
	Hard	99.5	Forged	345	550	10	(200)	3–5[2]	5
Ca	Soft	—	Cast	14	55	55	17HB	—	6
	Hard	—	Rolled	84.5	115	7	—	—	7
Co	Soft	99.9	Annealed	345–485	760	7–20	170	—	—
	Hard	99.9	25% reduction	—	1 135	0.5	320	—	—
Cr	V. pure soft	99.99	Iodide reduced; arc-cast swaged, annealed 600°C	—	415	44	230	—	8
	Soft	99.95[3]	Electrolytic; arc-cast, hot worked recrystallized above 900°C	—	103	0	130	—	8
	Hard	99.95[3]	Drawn ~500°C, 80–90% reduction	—	689	10	220	—	8
Hf	Soft	—	Iodide; hot rolled, 0–925°C; cold rolled, 5%; annealed 800°C for 1 h	240	445	43	(150–180)	—	9
	Hard	—	Iodide; extruded	365	745	20–27	—	—	7
Ir	Soft	—	Annealed	—	550–1 100	—	200–300	—	—
	Hard	—	Hot forged and swaged 800–1 500°C	—	1 200	13	650	—	10
Mo	V. pure, soft	99.99	Electron beam melted; hot rolled; recrystallized at 1 100°C for 1 h	345Y	435	5–25	—	—	8
	Soft	99.95[3]	Arc-cast; hot worked and recrystallized ~1 200°C	415–450Y	485–550	30–40	200	—	8
	Hard	99.95[3]	Rolled at about 1 000°C	550Y	620–690	10–20	250	—	8

Table 22.54 MECHANICAL PROPERTIES OF OTHER METALS OF INDUSTRIAL IMPORTANCE—*continued*

Metal	*Condition*	*Purity* %	*Heat treatment*	*Proof stress* MPa	*UTS* MPa	*Elong.* %	*Hardness* HV	*Impact strength* J	*Refs.*[1]
Nb	V. pure, soft	99.97	Electron beam melted, swaged recrystallized ~1 100°C	170	240	50	65	122–230	8, 11, 12
	Soft	99.9[3]	Arc-melted; cold forged; recrystallized for 4 h at 1 200°C	240	330	50	115	16–115[1]	8
	Hard	99.9[3]	Cold rolled ~90%	550	585	5	160	—	8, 11
Nb–Hf Ti (WC-103 alloy)	Annealed	Nb 89.0 Hf 10.0 Ti 1.0	1 H at 1 315°C 20°C 1 500°C 2 500°C	262 124 69	372 276 83	20 16 50	— — —	— — —	— — —
Nb–Hf–W–Y (WC-129Y)	Annealed	Nb 79.9 Hf 10.0 W 10.0 Y 0.1	1 H at 1 315°C	414	552	20	—	—	—
Nb–Zr	Annealed	Nb 99.0 Zr 1.0	1 H at 1 315°C	103	241	20	—	207	19
Nb–W–Zr (Nb-752)	Annealed	Nb 87.5 W 10.0 Zr 2.5	1 H at 2 315°C	379	517	20	—	—	—
Np	Soft	99.1	Cast	—	—	—	355	—	13
Os	Soft	—	Wrought and annealed	—	—	—	350	—	6
	Hard	—	Cold worked 7%	—	—	—	1 000	—	4
Pd	Soft	99.9	Wrought and annealed	34.5	140–195	24–40	40	—	4
	Hard	99.9	Wrought and cold worked	205	325	15	100	—	4
Pt	Soft	99.9	Wrought and annealed	14–35	125–145	30–40	40	—	4
	Hard	99.9	Wrought and cold worked ~50%	185	195–205	3	100	—	4
Pu	Soft	99.9	Cast (αPu)	205–310	310–550	1	260–270	3	14
Re	Soft	99.9	Sintered, swaged and annealed	315	1 125	24	280	—	8
	Hard	99.9	Cold rolled sheet, 30% reduction	2 150	2 225	2	700	—	8
Rh	Soft	—	Annealed, 900°C	69–275	690–760	20–40	120	—	15
	Hard	—	Cold rolled	—	1 380–2 070	—	300	—	4, 7, 15
Ru	Soft	99.9	Wrought and annealed at 1 500°C	372	495	3	350	—	15
	Hard	99.9	Wrought and cold worked 10%	—	—	—	750	—	4
Sc	Soft	—	—	—	—	—	78HB	—	16
	Hard	—	Cold swaged 22%	—	—	—	136HB	—	16

Table 22.54 MECHANICAL PROPERTIES OF OTHER METALS OF INDUSTRIAL IMPORTANCE—*continued*

Metal	*Condition*	*Purity* %	*Heat treatment*	*Proof stress* MPa	*UTS* MPa	*Elong.* %	*Hardness* HV	*Impact strength* J	*Refs.*[1]
Ta	V. pure, soft	99.98	Electron beam melted; cold rolled annealed 1 200°C	180	205	35–45	70–80	—	8
	Soft	99.95[3]	Recrystallized sheet	310–380	310–485	25–40	90	—	8, 11
	Hard	99.95[3]	Cold worked 95%	705	760	3	200	—	11
Th	Soft	~99.95	Iodide; wrought and annealed	48	115	36	38	41	7
	Hard	~99.95	Iodide, cold rolled	295	305	6	70	—	17
U	Soft	99.95	Coarse grained, cast	190	385	4	187	19	18
	Hard	99.95	Fine grained—rolled at 550°C —quenched from 722°C	250	580	9	250	15	18
U–Mo	As hot-rolled	Mo 2.0	Rolled 82% at 800°C	703	972	8	—	—	—
	As quenched	Mo 5.0	Quenched in water from 900°C	469	656	29	165	9.6	20
U–Mo Re	As quenched	Mo 4.0 Re 1.0	Quenched in water from 900°C	239	409	3	169	3.7	—
U–Ti	Extruded	Ti 0.75	Extruded at 800°C	537	1 111	12	—	—	—
	Precipitation hardened		Quenched in water from 900°C and aged at 350°C	876	1 420	20	—	320	—
V	V. pure soft	99.95	Iodide reduced: arc-melted, swaged and recrystallized	103	190	39	55	—	8
	Soft	99.8[3]	Calcium reduced: arc-melted, cold worked recrystallized	170–450	260–585	28–34	80	10–136	8
	Hard	99.8[3]	Cold worked	515–690	530–730	1–3	150	—	Several
W	Soft	99.95	Sintered rod; swaged and annealed, 1 590°C	550	550–620	0	360	—	8, 11
	Hard	99.95	Sintered, cold worked	—	1 920	0	500	—	11
Y	Soft	—	—	57Y	130	(25)	30–60HB	24	16
	Hard	—	50% cold swaged	375Y	455	2	100–140HB	—	16

[1] Where data exist from more than one source, ranges of values are given or, alternatively, if the values are similar a probable average is given.
[2] Unnotched Charpy.
[3] Principal impurities are interstitial O, C, N.
[4] Properties very sensitive to impurity content.
Y = 'Yield stress'.
() Interpolated from another source.
HB = Brinell.
HV = Vickers PN.

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22.12 Bearing alloys

Bearing alloys have to satisfy a number of criteria, depending on their application, of which the following are the more important.

WEAR RESISTANCE

The bearing must resist wear and more importantly must not cause wear of the mating surface. The stronger, harder bearing materials must therefore be operated against a hardened mating surface.

EMBEDDABILITY

When dirt or detritus from associated parts is present in the lubricant supply the bearing must minimize damage to the mating surface. Soft bearing materials can absorb more dirt than hard materials.

CONFORMABILITY

The misalignments inherent in mechanisms under load require an ability in the bearing to conform to the geometry of the mating surface. Softness and conformability in a bearing material also facilitate the creation of a hydrodynamic film of lubricant over the bearing surface under sparse lubrication conditions.

STRENGTH

Under static loads the bearing must have a yield strength greater than the applied load. Under dynamic fatigue or shock loads, a combination of high yield strength and ductility is required. The relative fatigue strengths of various bearing alloys can be seen from Figure 22.1 and mechanical properties from Table 22.55.

CORROSION RESISTANCE

The bearing material must resist corrosion by the atmosphere or by the lubricant.

THERMAL EXPANSION

The expansion coefficient of the bearing material must be sufficiently close to that of the housing for there to be no significant loss of interference fit at bearing operating temperatures.

It will be apparent that a bearing material is a compromise between the conflicting requirements for softness and strength, and the optimum compromise depends on the application. High effective strength from a relatively weak bearing material may be achieved if the material is present as a thin lining on a steel backing, and the majority of bearings have this construction. The copper-based engine bearing linings and the stronger aluminium alloys are overlay plated with a thin layer of lead–indium. This soft, partly sacrifical layer provides surface embeddability and conformability, and is thin enough (0.01–0.03 mm) to have good load carrying capacity.

Table 22.55 MECHANICAL PROPERTIES OF BEARING ALLOYS

	Nominal composition and manufacturing process						*Mechanical properties*			
Alloy	Al	Cu	Pb	Sb	Sb		*Proof stress* MPa	*UTS* MPa	*Elorgation* %	*Hardness* HV5
Copper base alloys	—	Rem	10	—	10	Sintered steel backed	249	303	5	120
		Rem	22	—	4.5	Sintered steel backed	81	121	5	46
	—	Rem	25	—	1.5	Sintered steel backed	75	112	5	45
		Rem	30		—	Sintered steel backed	62	93	5	34
	—	Rem	—	—	10	P 0.5% max. Continuously cast	233	420	16	120
	—	Rem	9.5	—	5	Continuously cast	155	280	15	70
	—	Rem	10	—	10	Sand cast	101	233	10	75
		Rem	20		5	Continuously cast	124	233	10	70
		Rem	26		2	Rotary lined on steel	62	110	3	48
Aluminium base alloys	Rem	1	—		20	Continuously cast steel backed	42	120	25	37
	Rem	1	—	—	6	Ni 1.0% Continuously cast steel backed	50	140	28	45
	Rem		—	—	40	Continuously cast steel backed	40	67	26	27
	Rem	1	—	—	—	Si 10.6% continuously cast steel backed	87	194	17	56
	Rem	1	—	—	6	Ni 1.0% Cold worked 4% Continuously cast	140	147	22	50
	Rem	1.5	—	—	6	Ni 1.4% Mg 0.9% Si 0.5% Continuously cast	83	207	10	78
	Rem	1	0.9	—	—	Zn 5% Si 1.5%	—	216	15	64
Whitemetals tin base	—	3.3		7.5	Rem	Cast on steel strip	65	76	10	27
	—	3.3		7.5	Rem	Rotary lined on steel	39	70	15	31
		3	—	7.7	Rem	Cd 1.25% Rotary lined on steel	76	90	8	32
Whitemetals lead base	—	0.5	Rem	15	1	As 1% Cast on steel strip and annealed	25	70	6	17
	—	—	Rem	10	6	Cast on steel strip and annealed	30	42	33	16
	—	0.5	Rem	10	10	Rotary lined on steel	60	73	8	25

Rem = Remainder. Properties are typical values.

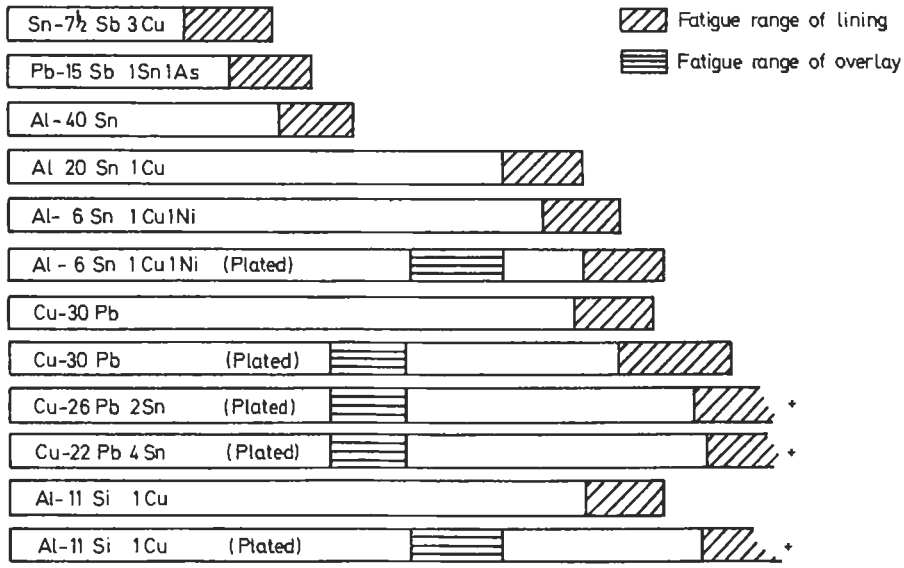


Figure 22.1 *Relative fatigue strength of bearing alloys. Back of bearing temperatures from* 70°C *to* 100°C

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23 Sintered materials

A wide range of useful metallic materials is made from powder by the process known as sintering. Such materials are commonly referred to as sintered materials, and individual engineering components made by the process are known as sintered parts, sintered components, or PM parts—PM or PM/M being the acronym for powder metallurgy.

23.1 The PM Process

This process consists of compacting the powder by means of pressure in a die or mould of prescribed shape; the compact thus formed must have sufficient green strength to allow it to be removed from the die and handled without fracture. This is an important property. After removal from the die, the compact is heated, normally in a protective atmosphere or vacuum, to a temperature usually below the melting point, such that the particles weld together and densify markedly increasing the strength. This is the step known as sintering. In some cases, especially when the sintered compact is to be subsequently rolled or extruded, isostatic compaction in a flexible mould is used. An exception to the compaction process is the production of filter elements from spherical powders, often of bronze, by what is known as loose powder sintering, in which powder is poured into a mould of the appropriate shape and sintered in the mould.

Increasingly, sintered billets are being made for subsequent mechanical working such as hot extrusion or rolling. These processes yield wrought material to which the name sintered parts does not apply, but the bulk of PM products are items made individually to the final shape and size.

23.2 The Products

The main classes of PM products are:

1. Engineering components, i.e. parts for machinery made by directly pressing in rigid dies of the required shape, and sintering with either no or only minor further shaping. This is the largest and most familiar class of PM product.
2. Refractory metals. These often have melting points that are inconveniently high and/or are difficult or impossible to work in the cast state because they are brittle. This group includes tungsten, molybdenum, tantalum, and related metals.
3. Intentionally porous materials for use as filters or as oil-retaining (self-lubricating) bearings.
4. Composites. These may consist of two or more metals that are insoluble in each other in the solid state, but the name is generally used to signify a metal in which is dispersed one or more non-metallic ingredients such as refractory oxide, carbide, or other compound that is insoluble in the metal. These are referred to as metal matrix composites. A very important member of this group, the hardmetals, is the subject of a later section.
5. High-duty alloys in wrought form having mechanical properties superior to those of the corresponding material made from ingot. In this category must be included certain composite materials having fine dispersions of oxide or the like designed to improve the strength, especially at elevated temperatures. In some other cases the principal reason for making wrought products from powder is that higher yields of usable material are possible. This applies to metals such as titanium alloys the scrap from which cannot readily be re-used.
6. Magnetic materials. This very important class of sintered material is dealt with in Chapter 20.

23.3 Manufacture and Properties of Powders

23.3.1 Powder manufacture

There is a large number of possible ways of making metal powders, the principal ones used on a commercial scale for powders for PM being:

— Solid state reduction of a compound of the metal, commonly the oxide. This often results in a loosely caked sponge which is converted into powder by milling.

— Thermal decomposition of a compound of the metal. This also may yield a sponge.

— Electrolysis. By suitable choice of the various parameters certain metals can be deposited in a spongey or powder form. Such powders are often dendritic. In the case of iron, a dense deposit is formed which is reduced to powder by comminution.

— Atomization, in which molten metal is disintegrated into small drops which are caused or allowed to solidify out of contact with each other and with any solid surface. There are many ways in which the molten droplets may be produced, the most common being to allow a stream of molten metal to fall vertically from a tundish into a chamber where it is broken up by jets of high-pressure liquid or gas. Another process now gaining in importance is centrifugal atomization, in which droplets are flung from a rapidly rotating pool of molten metal or from a disk on to which a thin stream of metal impinges. In another process the end of a rotating bar is progressively melted and if the heating is by laser beam or plasma arc the process can be carried out in near vacuum, thus substantially eliminating the risk of contamination. This is called REP (Rotating Electrode Process) and if a plasma arc is used PREP (Plasma REP). An important feature of atomization is that it can produce homogeneous fully pre-alloyed powders.

Table 23.1 lists the powder production processes used for many of the metals used in PM.

— Rapid solidification. This means cooling molten metal at a very high rate such that on solidification an amorphous or other non-equilibrium structure results. In the case of certain aluminium alloys, for example, it is possible to hold in solution significantly higher percentages of alloying elements (see Table 23.2). If a rapidly solidified alloy is consolidated by a powder metallurgical process that does not involve heating to a temperature high enough to induced recrystallization, wrought material with substantially improved mechanical properties may result. The processes used mostly involve projecting molten metal to form a very thin film on a rotating water cooled cylinder to produce flake or ribbon which is crushed to powder.

— Mechanical alloying. Another way of achieving higher strength and especially retention of that strength at elevated temperatures is to include in the metal matrix a finely dispersed insoluble

Table 23.1 PRODUCTION PROCESSES FOR METAL POWDERS
The most widely used method is put first.

Aluminium	Gas atomization (usually air), Comminution
Beryllium	Comminution, electrolysis
Brass	Atomization—water or gas
Bronze	Water atomization for irregular powder, Air atomization for spherical powder
Cobalt	Oxide reduction
Copper	Water atomization, electrolysis. (Both are in general use)
Iron: unalloyed	Oxide reduction, water atomisation, electrolysis
Iron: cast	Comminution
Molybdenum	Oxide reduction—by hydrogen
Nickel	Thermal decomposition of the carbonyl, reduction of a salt in solution
Nickel alloys inc. superalloys	Atomization—inert gas, centrifugal
Platinum	Thermal decomposition of a salt
Silver	Precipitation from solution of a salt, usually by an organic reducing agent
Silver alloys	Atomization
Steels	Atomization—usually with water
Tin	Air atomization
Titanium	Reduction of the chloride by magnesium, Thermal decomposition of the hydride
Tungsten	Reduction of the oxide—by hydrogen

Note: Powders of practically all metals can be produced by atomization—the table lists the processes common in present day commercial practice.

Table 23.2 EXTENDED SOLUBILITY IN ALUMINIUM VIA RAPID SOLIDIFICATION

Additive	*Maximum equilibrium solubility, at. %*	*Observed maximum by rapid quenching*
Cu	2.5 (at 821 K)	18
Mn	0.7 (at 923 K)	9
Si	1.6 (at 850 K)	16

phase, commonly a stable oxide. Oxide Dispersion Strengthened (ODS) materials are increasingly of interest in aerospace technology, and they are of necessity made by PM. In general the improvement is greater the finer the particles of the dispersed phase, the mechanism being dislocation locking as in precipitation hardening. An approach near to ideal is mechanical alloying, in which a metal powder is mixed with a fine oxide powder and the mixture milled for several hours or even days usually in an attritor, during which process the oxide is beaten into the metal, the particles of which are repeatedly flattened, broken up, and reflattened while at the same time the oxide particles are broken down into progressively smaller fragments, typically less than 100 nm. Mechanically alloyed powders are generally consolidated and converted into wrought shapes.

23.3.2 Properties of metal powders and how they are measured

Chemical composition

Chemical composition is the main factor that determines the properties of the finished material. One feature that is specific to powders is the oxide layer on the surface of the particles. This has an important influence of the green strength of compacts but more especially on the sintering process which depends on the formation of true metallurgical bonds between adjacent particles. In the case of metals with easily reducible oxides the level of surface oxide is determined by heating a weighed sample in hydrogen under specified conditions, cooling in hydrogen, and weighing. The reduction in weight is commonly called the loss in hydrogen or hydrogen loss. The procedure gives a misleading figure if volatile material is present, such as organic additions (pressing lubricants), moisture, or volatile metals such as zinc. The process is not applicable to metals with very stable oxides that are not reducible in this way, nor to alloys containing a high percentage of metals such as aluminium, titanium, chromium, and stainless steels. Table 23.3 gives the specified reduction conditions for some common metals.

Particle size and size distribution

The meaning of size is complicated by the enormous variety of shape of particles which makes quantitative assessment difficult. Volume, maximum linear dimension, average dimension, cross

Table 23.3 CONDITIONS FOR DETERMINATION OF LOSS IN HYDROGEN

Metal powder	*Reduction temperature* °C	*Reducation time* min
Tin bronze	775 ± 15	30
Cobalt	1 050 ± 20	60
Copper	875 ± 15	30
Copper lead[1] and leaded bronze[1]	600 ± 10	10
Iron	1 150 ± 20	60
Alloyed steel	1 150 ± 20	60
Lead[1]	550 ± 10	30
Molybdenum	1 100 ± 20	60
Nickel	1 050 ± 20	60
Tin	550 ± 10	30
Tungsten	1 150 ± 20	60

[1] Results should be interpreted with caution.

sectional area are different measurements which can be made. A considerable range of techniques is or has been used, including among others microscopical examination, elutriation, sedimentation, light obscuring, and light scattering, but for most PM powders the process normally used is sieving through wire mesh screens. The former designation of screen size by the number of strends of wire per unit length has been superseded by specifying the aperture size in terms of the largest sphere that will pass through it. However the older designation is still used and Table 23.4 shows the relationship between the various standards. The less equiaxed the particles the less meaningful will be the result of a sieve test. For example in the extreme case of an acicular powder, the length rather than the diameter is likely to be the controlling dimension. Nevertheless, meaningful and useful results are obtained, especially when different batches of nominally similar powder are being compared. For very fine, so called subsieve size powders other methods have to be employed. In common use are the Fisher subsieve sizer which is based on the permeability to gas of a bed of powder, and the BET method which is based on gas absorption. This measures in effect the total surface area.

Apparent density (AD) This most important property is in a general sense the same as bulk density, i.e. it is the mass of a unit volume of powder, but the method and apparatus used to determine it need to be carefully specified if consistent results are to be obtained. The test normally specified—ISO 3923/1—is to allow the powder to emerge from a funnel through a specified orifice into a cylindrical cup of specified dimensions which overflows. The surplus is carefully removed by drawing a straight edge across the top of the cup, the powder in the cup then being weighed. The apparatus used is specified in ISO 3923/1 and illustrated in Figure 23.1. (The same apparatus is also used to determine the flow properties of powders.) AD is of importance in several ways but especially in that it determines the amount, i.e. mass, of powder in the die before compaction.

Flow factor In the commercial production of compacts, powder is fed automatically into the die cavity and must, therefore, flow readily. The flowability is measured by timing the flow of 50 g of powder from a funnel of specified geometry and the result expressed in seconds. The procedure is laid down in ISO 4490, the apparatus being generally referred to as the Hall flowmeter after its designer (Figure 23.1). The properties of some widely used PM grade powders are given in Tables 23.5 and 23.6

23.4 Properties of Powder Compacts

Apart from dimensions which are, of course, of major importance in the manufacture of individual PM parts, the relevant properties of compacts are density and strength. Green density as it is called has a marked influence on green strength and also largely determines the final, i.e. sintered, density. It is determined by Archimedes principle. Green strength is the term used to indicate the strength of a compact and two standard methods are in general use for measuring it.

1. A three point bend test on a standard compact of rectangular cross section gives the Transverse Rupture Strength—ISO 3995.
2. A compression test on the diameter of a ring shaped compact gives the Radial Crushing Strength (K factor)—ISO 2739. This test applies especially to cylindrical bearings. The k factor is given by the formula: $(K = F(D-e)/Le^2$ N/mm^2, where F = breaking load in Newtons, L = the length in mm, D = the external diameter in mm, E = the wall thickness in mm.

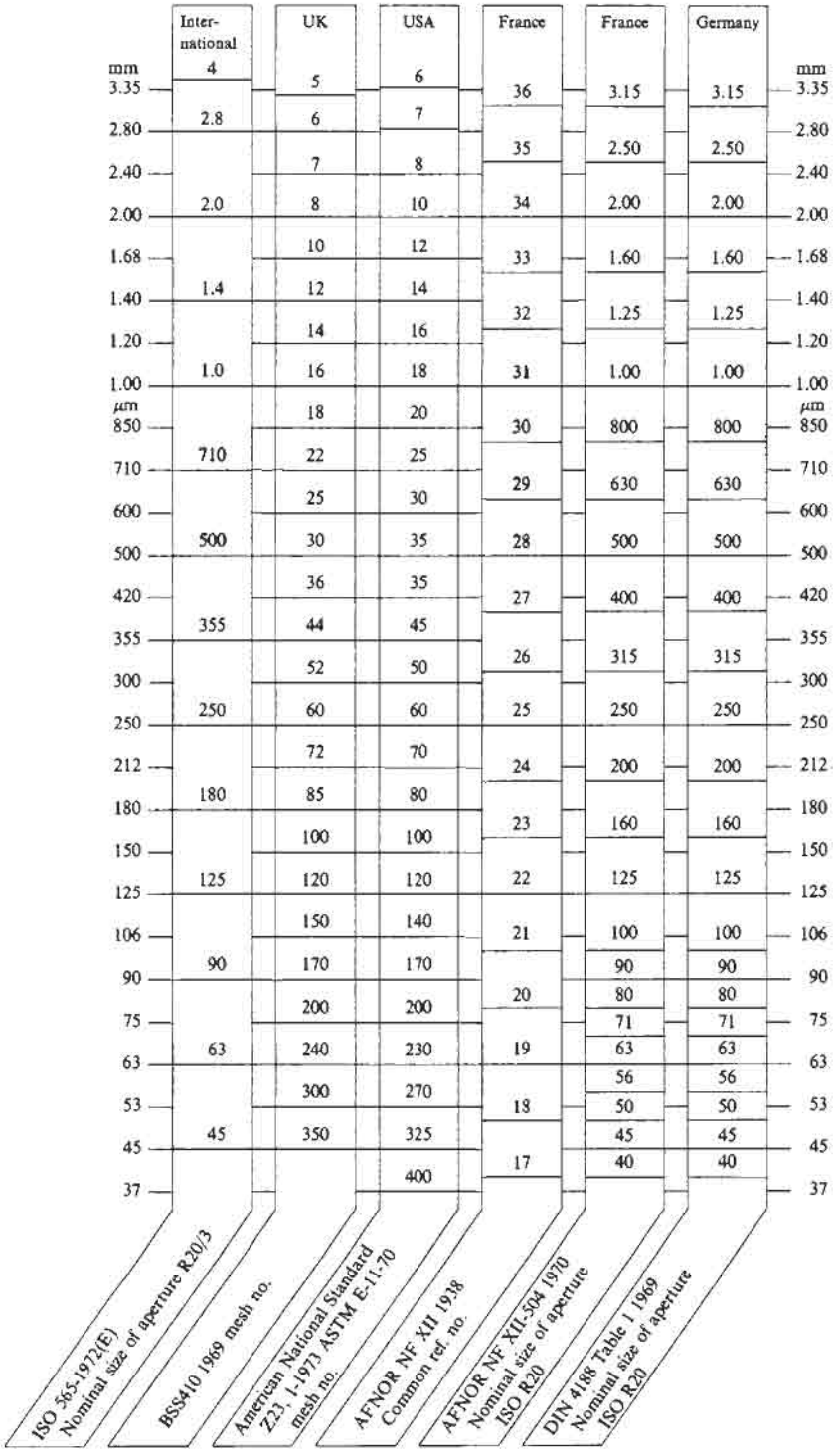
Compressibility (compactibility) For economic as well as technical reasons it is desirable to use as low a pressure as possible to achieve the required compact density, therefore the compressibility of the powder is of considerable importance. This factor is usually expressed either as the density obtained with a given compacting pressure (see Table 23.6) or is shown as a curve relating density to pressure. Compressibility as defined in this way is influenced by the AD of the powder and by the actual strength of the particles. Thus an alloy powder will have a lower compressibility than that of a pure metal. For this reason it is often preferred to use mixtures of elemental powders rather than pre-alloyed powders of the composition ultimately required.

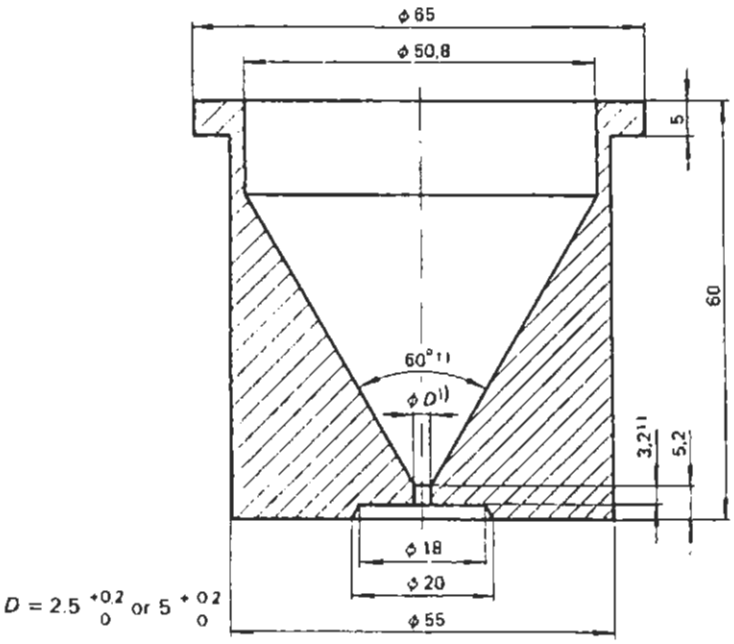
23.5 Sintering

Most PM parts (other than hardmetals) are sintered in continuous furnaces normally having three zones:

1. A pre-heating or de-waxing zone in which the lubricant is driven off.

Table 23.4 COMPARISON TABLES OF STANDARD SIEVES





[1] These values are mandatory.

Dimensions in millimetres

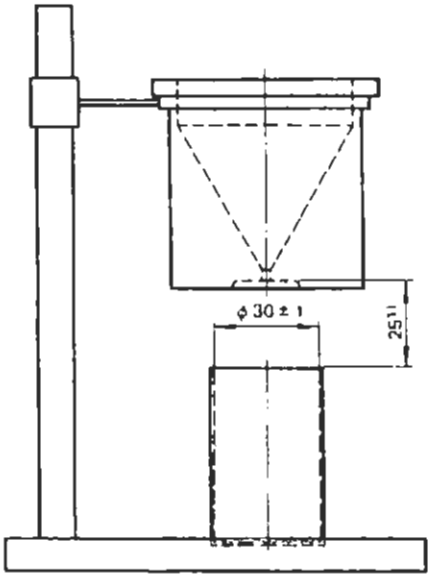


Figure 23.1 *The Hall flowmeter*

Table 23.5 PROPERTIES OF ELECTROLYTIC COPPER POWDERS

Grade	*OS*	*SA*	*NQ*	*R*	*PD*	*MER*	*HF*
Chemical content							
Copper (typical)	99.5%	99.5%	99.5%	99.5%	99.5%	99.5%	99.5%
Oxygen	0.1% max	0.1% max	0.1% max	0.1% max	0.15% max	0.15% max	0.15% max
Physical							
App. density g/cm^3	2.60–2.75	2.40–2.55	2.55–2.70	2.50–2.65	2.30–2.45	2.45–2.60	2.60–2.75
Flow factor s/50 g	30 max	32 max	32 max	35 max	38 max	38 max	38 max
Radial change indication	+2.2%	+1.75%	+1.75%	+1.35%	+0.75%	+0.75%	+0.75%
Granulometry							
Mesh *Micrometre*							
+85 +180	Trace	Trace	Trace	Trace			
+100 +150	3% max	2% max	2% max	1% max	Trace	Trace	Trace
+150 +106	10–20%	5–15%	5–15%	0–10%	5% max	5% max	5% max
+200 +75	25–35%	20–30%	20–30%	10–20%	10–25%	10–25%	10–25%
+240 +63	10–20%	5–15%	5–15%	5–15%	0–10%	0–10%	0–10%
+350 +45	15–25%	15–25%	15–25%	15–25%	10–25%	10–25%	10–25%
−350 −45	20–35%	30–45%	30–45%	40–55%	50–65%	50–65%	50–65%

Radial change indications are those expected from normal bearing manufacturing processes.

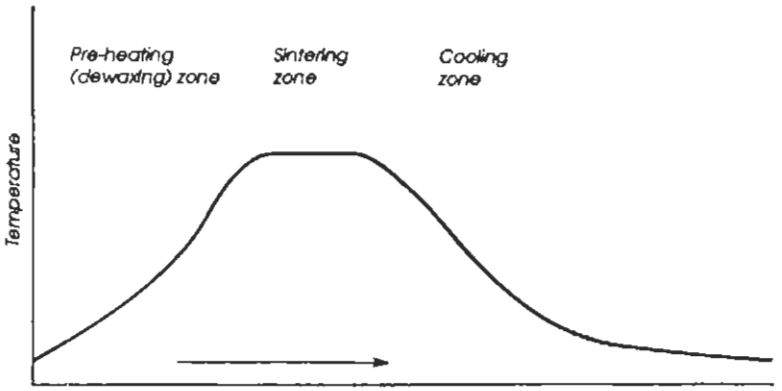


Figure 2

2. The sintering zone proper, the temperature of which is called the sintering temperature.
3. A cooling zone normally surrounded by a water jacket. Figure 23.2 shows a typical temperature profile for the work load.

Compacts of pure metals and of fully pre-alloyed alloys shrink during sintering, the amount of shrinkage being dependent on the green density and the sintering regime, i.e. temperature and time. With mixtures of elemental powders or of alloys of different compositions, the situation is different. Diffusion effects can cause an actual expansion to occur initially and this feature can be used to provide mixes that neither shrink nor grow on sintering. The dimensional change on sintering is, of course, one of the major factors that determine the consistency of dimensions of the sintered component. It is in most cases the ability to produce components directly, i.e. without any subsequent machining, that provides the economic justification for making them from powder.

In the case of large compacts that are intended to be subsequently wrought into sheet, rod, or wire, these factors are of little or no importance.

23.6 Ferrous Components

Iron-based materials account for the bulk of PM parts and they range in composition from nearly pure iron through low alloy steels to stainless steels and high-speed steels for cutting tools, etc. It

Table 23.6 PROPERTIES OF PM GRADE SPONGE IRON POWDER

	NC100.24 *Typical data*	*Testing method*
Apparent density/g/cm³	2.45	ISO 3923-1977
Flow/s/50 g	29	ISO 4490-1978
Sieve analysis/%		ISO 4497-1983
+208 μm	0	
+147 μm	5	
−43 μm	19	

Compressibility/g/cm³ — ISO 3927-1977

Comp. pressure	1	2
4.2 t/cm²	6.55	6.63
300 MPa	6.09	6.25
500 MPa	6.79	6.83
700 MPa	7.12	7.0

1. Lubricated die
2. 0.6% Kenolube P11 on 0.8% Zn-st

Green strength/N/mm²

Comp. pressure	1	2	3
300 MPa		14	10
500 MPa	45	24	18
700 MPa		30	23

1. Lubricated die
2. 0.6% Kenolube P11
2. 0.8% Zn-st

Chemical analysis/%

Carbon	0.01	ISO 4491-1978
H_2-loss	0.20	ISO 7625-1983

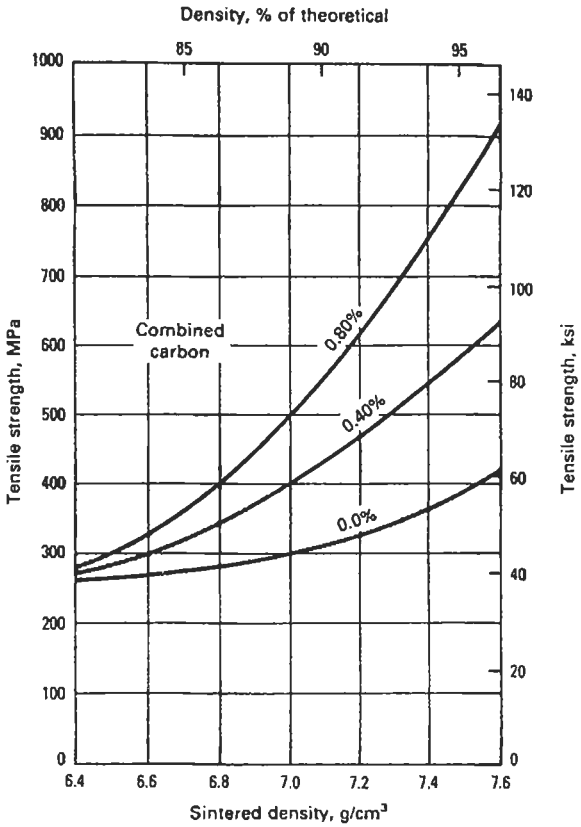


Figure 23.3 *Effect of density on strength of as-sintered 4% nickel steel*

should be noted, however, that as regards low-alloy steels the compositions used differ from those of ingot-based metal. The reason for this is that alloying elements that give rise to oxide films that are stable in normal sintering atmospheres and which therefore inhibit sintering are not much used. Such elements include manganese, chromium, and silicon. Favoured compositions for sintered steels contain, in addition to carbon, one or more of the elements copper, nickel and molybdenum, the oxides of which are readily reducible by hydrogen. In addition there are compositions containing up to 0.6% of phosphorus.

Sintered steels differ from wrought in strength in that the hardness, strength, and ductility depend not only on composition and state of heat-treatment, but also markedly on density (see Figure 23.3). Considerable effort has been put into ways of increasing the density of sintered parts in order to extend their use to more heavily stressed applications. Ways of doing this are:

1. Re-press and re-sinter.
2. Re-press at elevated temperature.
3. Hot forge.

In the third process, called sinter forging or powder forging, a sintered blank of appropriate geometry is hot forged in a closed die to the required shape and dimensions. In this way it is possible to achieve properties as good as those of wrought steels and in some respects better because of the complete homogeneity and isotropy of the material (see Table 23.7). Accuracy too may be superior because it is possible to maintain closer tolerances on the mass of the blank than is normal with blanks cut from bar. Flash should be completely absent. Another way of increasing the density is to fill the voids with copper or a dilute copper alloy which is melted on the surface and absorbed into the pores. This process, known as liquid infiltration, is liable to affect adversely the dimensional accuracy.

Table 23.7 MECHANICAL PROPERTIES OF SINTER-FORGED STEEL FOR P/F-4600 MATERIALS (Mn 0.10–0.25, Ni 1.75–1.90, Mo 0.50–0.60)
Sintered at 1120°C in dissociated ammonia unless otherwise noted.

Forging mode	*Carbon, %*	*Oxygen, ppm*	*Ultimate tensile strength* MPa	*0.2% offset yield strength* MPa	*Elongation % in 25 mm*	*Reduction of area, %*	*Room temperature Charpy V-notch impact energy* J	ft lb	*Core hardness,* HV30	*Fatigue endurance limit* MPa	*Ratio of fatigue endurance to tensile strength*
Blank carburized											
Upset	0.24	230	1565	1425	13.6	43.2	16.3	12.0	487	565	0.36
Re-press	0.24	210	1495	1325	11.0	34.3	12.9	9.5	479	550	0.37
Upset[a]	0.22	90	1455	1275	14.8	46.4	22.2	16.4	473	550	0.38
Re-press[a]	0.25	100	1455	1280	12.5	42.3	16.8	12.4	468	510	0.36
Upset[b]	0.28	600	1585	1380	7.8	23.9	10.8	8.0	513	590	0.37
Re-press[b]	0.24	620	1580	1305	6.8	16.9	6.8	5.0	464	455	0.29
Quenched and stress relieved											
Upset	0.38	270	1985	1505	11.5	33.5	11.5	8.5	554	—	
Re-press	0.39	335	1960	1480	8.5	21.0	8.7	6.4			
Upset	0.57	275	2275		3.3	5.8	7.5	5.5	655	—	
Re-press	0.55	305	1945		0.9	2.9	8.1	6.0	—	—	
Upset	0.79	290	940	—	0.0	0.0	1.4	1.0	712	—	—
Re-press	0.74	280	1055		0.0	0.0	2.4	1.8	—		—
Upset	1.01	330	800	—	0.0	0.0	1.3	1.0	672		—
Repress	0.96	375	760	—	0.0	0.0	1.6	1.2	—	—	
Quenched and tempered											
Upset[c]	0.38	230	1490	1340	10.0	40.0	28.4	21.0	473	—	—
Re-press[c]	—		1525	1340	8.5	32.3	—	—	—	—	—
Upset[d]	0.60	220	1455	1170	9.5	32.0	13.6	10.0	472		—
Re-press[d]	—		1550	1365	7.0	23.0	—	—			—
Upset[e]	0.82	235	1545	1380	8.0	16.0	8.8	6.5	496		—
Re-press[e]	—	—	1560	1340	6.0	12.0	—	—		—	
Upset[f]	1.04	315	1560	1280	6.0	11.8	9.8	7.2	476	—	
Re-press[f]	—	—	1480	1225	6.0	11.8	—	—			—
Upset[g]	0.39	260	825	745	21.0	57.0	62.4	46.0	269		
Upset[g]	0.58	280	860	760	20.0	50.0	44.0	32.5	270		
Upset[h]	0.80	360	850	600	19.5	46.0	24.4	18.0	253	—	—
Upset[i]	1.01	320	855	635	17.0	38.0	13.3	9.8	268	—	—

[a] Sintered at 1260°C in dissociated ammonia. [b] Sintered at 1120°C in endothermic gas atmosphere. [c] Tempered at 370°C. [d] Tempered at 440°C. [e] Tempered at 455°C. [f] Tempered at 480°C. [g] Tempered at 680°C. [h] Tempered at 695°C. [i] Tempered at 715°C.

23.7 Copper-Based Components

There is a relatively limited market for structural components made of bronze, brass, or copper itself, copper usually being used for electrical applications, There is, however, a considerable market for oil-retaining bronze bearings and for (porous) filter elements. As regards bearings there is a conflict between the oil capacity which increases as the density decreases, and strength which increases as the density increases. The oil content normally lies between 15 and 30% by volume. Table 8 lists specified compositions and properties of several standard types of bearing including those made of iron or its alloys. Figure 4 shows the relationship between strength and sintering temperature for bronze bearings, and Figure 5 shows how the diameter varies with temperature.

23.8 Aluminium Components

The sintering of pure aluminium is impossible by reason of the tenacious oxide film present on the surfaces of the particles which cannot be reduced by any feasible sintering atmosphere. However, if certain alloying elements are present the alloy may have a significant gap between the solidus and liquidus temperstures so that sintering may be carried out just above the solidus and a liquid phase is present; this breaks down the surface oxide films and allows interparticle welding to take place. This is a typical example of what is called liquid phase sintering. As with copper based materials, the quantity of sintered aluminium components is relatively small, but they find application where lightness, corrosion resistance, or electrical or thermal conductivity are controlling requirements. The properties of some sintered aluminium alloys are given in Table 23.9.

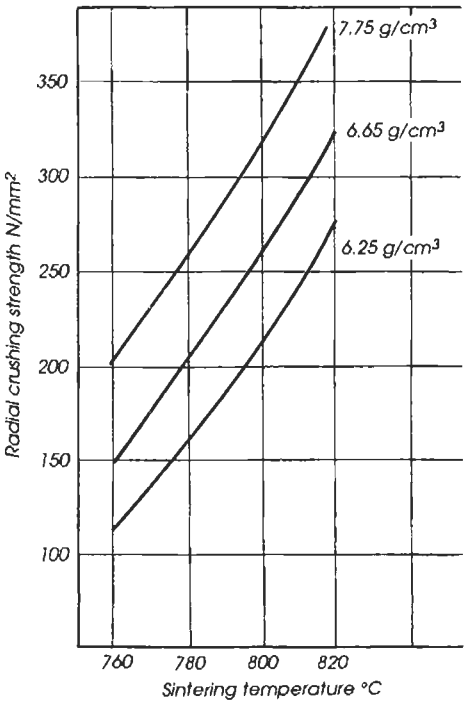


Figure 23.4 *Effect of sintering temperature on the strength of sintered bronze bearings*

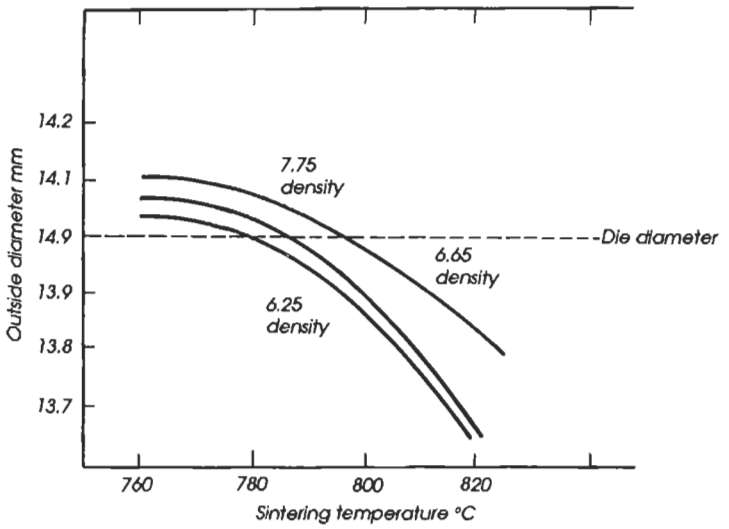
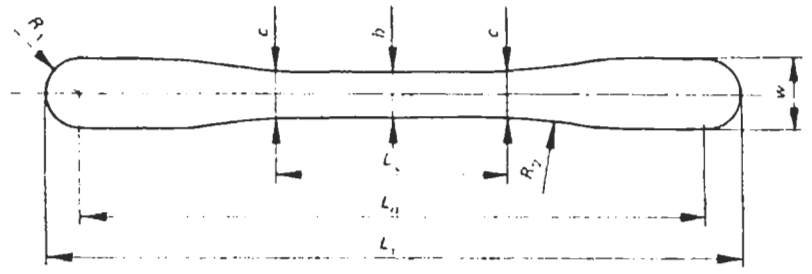


Figure 23.5 *The effect of sintering temperature on the diameter of bronze bearings*

23.10 Determination of the Mechanical Properties of Sintered Components

The properties of interest to users are the same as those of cast or wrought metal, but the measurement of hardness especially requires some elaboration because of the porous nature of sintered metal.

1. Hardness. A traditional indentor will make a larger impression and therefore record a lower hardness than that of dense metal of the same composition because the pore offer no resistance to deformation. A distinction is, therefore, made between apparent hardness as measured in a standard test, and true hardness, i.e. that of the same metal in the pore-free state. True hardness may be measured using a micro indentor and a carefully specified technique which minimizes the risk of the result being falsified by the porosity. Apparent hardness is related to strength in the same way as with dense materials; true hardness is relevant to wear resistance.
2. Strength. Strength is determined by tensile test, but because sintered parts are normally quite small it is rarely possible to cut test pieces from the parts themselves. It is standard practice, therefore, to produce separate test pieces compacted to the same density as a batch of parts and to sinter them along with the batch. Figure 22.6 shows the standard test piece.



b	c	L_c	L_e	L_1	w	R_1	R_2
5.70 ±0.02	n+0.25	32	81.0 ±0.5	89.7 ±0.5	8.7 ±0.2	4.35	25

Figure 23.6 *Standard tensile test piece* (ISO 2740). *Dimensions in mm*

Table 23.8 OIL-REPLACING BEARINGS

Material grade	Type	Bearing specifications: Chemical composition: Cu %	Sn %	Graph. %	Fe %	Others % max.	Density g/cm³	Typical oil content % v/v	K factor MPa min.	Maximum static load MN/m²	Related specifications: ISO 5755/1	BS 2590	Sint	SAE	AFNOR
60H	Bronze	Bal.	10	1.5	—	2	5.8–6.2	27	120	52	P4021Z	A110		840	FU–E10–58
63H	Bronze	Bal.	10	1.5	—	2	6.1–6.5	24	155	69	P4022Z	A111	A51	841	FU E10 62
68H	Bronze	Bal.	10	1.5	—	2	6.6–7.0	18	200	100	P4023Z	A112	B51	842	—
70Q	Bronze	Bal.	10	—	2	6.8–7.2	18	210	105	105	P4013Z	A113	850	—	—
58I	Iron		—	—	Bal.	2	5.6–6.0	23	170	70	P1012Z	A200	A00	B50	FC10–56
58T	Iron/copper	2			Bal.	2	5.6–6.0	23	200	100	P2012Z	A300	A10		F10–U3–56
58J	Iron/bronze	45	5		Bal.	2	5.6–6.0	27	100	52	—		—		—

Table 23.9 MECHANICAL PROPERTIES OF SINTERED ALUMINIUM ALLOYS

Family	Material grade	Composition in weight % (Al = the remainder): Mg	Si	Cu	Mn	Zn[1]	Cr	Density g/cm³	Relative density class	Hardness	Mechanical properties[1]: Tensile strength MPa	Yield strength MPa	Elongation %	Impact strength[2] J	Fatigue limit MPa	En GPa	Poisson's ratio	Symbol
2000	*[3]	1	0.3	2	—	—	—	2.53	6	83 HRH	140	100	4	—	—	—	—	PA 506Y
	*T6[4]	"	"	"	—	—	—	"	6	73 HRE	230	190	2	—	—	—	—	PA 506A
	**[3]	—	—	4	—	—	—	2.64	7	—	160	75	10	—		57	0.25	PA 207Y
	**T6	—	—	"	—	—	—	"	7	—	225	145	7	—	—	57	0.25	PA 207Y
	2014	0.5	0.8–1	4.4	<0.4	—	—	2.50	5	70 HRE	150	115	3	5	—	49	0.23	PA 615Y
	"	"	"	"	"	"	—	2.64	7	75 HRE	180	150	3	7	45	59	0.25	PA 617Y
	2014 T6	"	"	"	"	—	—	2.50	5	85 HRE	250	235	1	3	—	49	0.23	PA 615A
	"	"	"	"	"	—	—	2.64	7	90 HRE	300	280	2	6	52	59	0.25	PA 617A
6000	6061	1	0.6	0.25	—	—	0.1	2.42	6	62 HRE	100	65	4	7		47	0.23	PA 406Y
		"	"	"	—	—	"	2.55	8	65 HRH	125	80	6	—	35	56	0.25	PA 408Y
	6061 T6	1	0.6	0.25	—	—	0.1	2.42	6	72 HRH	140	130	0.5	2.5	45	47	0.23	PA 406A
		"	"	"	—	—	"	2.55	8	80 HRE	210	195	2	—		56	0.25	PA 408A
	***[3]	0.6	0.4	—	—	—	—	2.42	6	64 HRH	120	55	9	—	—	45	0.23	PA 306Y
		"	"	—	—	—	—	2.55	8	-	130	60	9		—	54	0.25	PA 308Y
	***T6	0.6	0.4	—	—	—	—	2.42	6	-	175	165	2	—	—	45	0.23	PA 306A
		"	"	—	—	—	—	2.55	8	-	185	170	3	—	—	54	0.25	PA 308A
7000	7075	2.5	—	1.6	—	5.6	0.2	2.51	6	90 HRH	205	150	3	—	—	49	0.23	PA 806Y
	7075 T6	"	—	"	-	"	"	2.51	6	80 HRE	310	275	2	—	—	49	0.23	PA 806A

[1] Mechanical properties obtainable after sizing. [2] IZOD impact test. [3] Non-standard compositions. [4] T6 = solution hardening and artificial ageing.

3. Impact. The presence of porosity has a very deleterious effect on impact properties and it is not common practice to measure this property.

The compositions and mechanical properties of the standard PM materials are shown in Tables 23.10–23.15.

23.11 Heat Treatment and Hardenability of Sintered Steels

Sintered steels can be hardened and tempered in the same way as wrought steels (see Figure 23.7), but the use of salt baths is not recommended because of the difficulty of removing the salt from the pores. The porosity has a marked effect on hardenability as shown in Figure 23.8. This is a consequence of the lowering of the thermal conductivity.

23.12 Case Hardening of Sintered Steels

Here also the porosity has a significant effect. In carburizing, nitriding, and carbo-nitriding, the gas enters the pores so that for a given regime the depth of hardening is greater and the transition

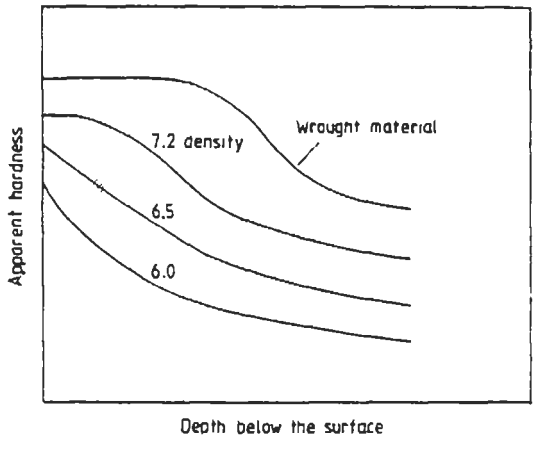


Figure 23.7 *Hardenability as a function of density and quench tests*

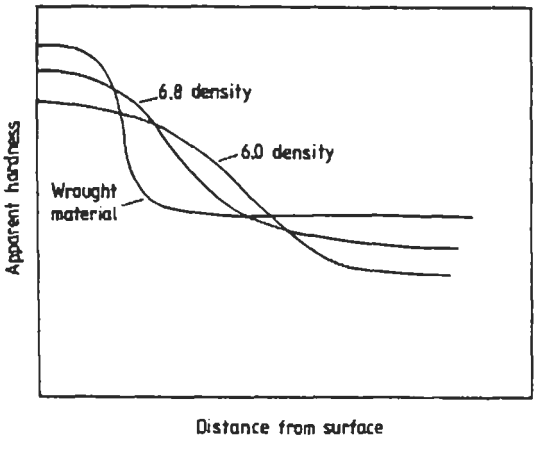


Figure 23.8 *Effect of porosity on the case hardening*

Table 23.10 IRON, CARBON STEELS, AND COPPER STEELS

		Mandatory values				*Informative approximate values*							
		Chemical composition				*Mechanical and physical properties*							
Materials	*Grade*	*C combined* %	*Cu* %	*Fe* %	*Total other elements (max.)* %	*Density (min.)* g/cm³	*Ultimate Tensile strength (min.)* MPa	*Apparent hardness (min.) HV 5*	*Relative density* %	*Yield strength (0.2% offset)* MPa	*Elongation*[2] %	*Apparent surface hardness after appropriate treatment*[3] *HV 5*	*Apparent hardness Rockwell*
Iron	P1022-	<0.3		Balance	2	5.6	70	30	75	40	1		30 HRH
	P1023-					6.0	100	40	80	60	2		70 HRH
	P1024-					6.4	140	50	85	80	3		80 HRH
	P1025-					6.8	180	65	94	120	6	400	15 HRB
	P1026-					7.2	220	80	94	120	6	500	30 HRB
Carbon steel	P1033-	0.3 to 0.6		Balance	2	6.0	140	55	80	90	nm		20 HRB
	P1034-					6.4	190	75	85	120	1		45 HRB
	P103-					6.8	240	90	90	130	2	400	60 HRB
	P1042-	0.6 to 0.9		Balance	2	5.6	150	55	75	120	nm		35 HRB
	P1043-					6.0	200	80	80	160	nm		50 HRB
	P1044-					6.4	250	100	85	210	1		65 HRB
	P1045-					6.8	300	120	90	250	1	400	75 HRB
Copper steel	P2022-	<0.3	1 to 4	Balance	2	5.6	120	45	75	90	nm		70 HRH
	P2023-					6.0	160	55	80	120	1		80 HRH
	P2024-					6.4	200	65	85	140	2	300	15 HRH
	P2025-					6.8	240	75	90	170	3	450	25 HRB
	P2032-	<0.3	4 to 8	Balance	2	5.6	160	60	75	120	nm		80 HRH
	P2033-					6.0	200	75	80	140	nm		90 HRH
	P2034-					6.4	240	85	85	190	1		20 HRB
	P2035					6.8	280	95	90	230	2	400	30 HRB
Copper carbon steel	P2043-	0.3 to 0.6	1 to 4	Balance	2	6.0	220	80	80	190	nm		45 HRB
	P2044-					6.4	280	100	85	230	nm	350	60 HRB
	P2045-					6.8	350	120	90	280	1	450	75 HRB
	P2053-	0.6 to 0.9	1 to 4	Balance	2	6.0	270	100	80	210	nm		60 HRB
	P2054-					6.4	340	120	85	270	nm	350	70 HRB
	P2055-					6.8	420	140	90	330	nm	450	80 HRB
	P2063-	0.3 to 0.6	4 to 8	Balance	2	6.0	250	90	80	210	nm		60 HRB
	P2064-					6.4	320	110	85	260	nm	350	70 HRB
	P2073-	0.6 to 0.9	4 to 8	Balance	2	6.0	300	110	80	240	nm		65 HRB
	P2074-					6.4	360	130	85	280	nm	350	75 HRB

[1] These materials may be supplied with additives to increase machinability, the properties given remain unchanged.
[2] nm = not measurable.
[3] These hardness values are obtainable from materials that have undergone a suitable hardening process. The values of all other properties, with the exception of density and copper content, will not then apply.

Table 23.11 NICKEL STEELS AND NICKEL–COPPER STEELS (AS SINTERED)

		Mandatory values											*Informative approximate values*
		Chemical composition					*Mechanical and physical properties*						
Materials	*Grade*	*C combined* %	*Ni* %	*Cu* %	*Fe* %	*Total other elements (max.)* %	*Density (min.)* g/cm^3	*Ultimate Tensile strength (min.)* MPa	*Apparent hardness (min.) HV 5*	*Relative density* %	*Yield strength (0.2% offset)* MPa	*Elongation*[2] %	*Apparent hardness Rockwell*
Nickel steels[1,2]	P3014-	<0.2	1 to 3	<0.8	Balance	2	6.4	200	50	85	140	6	35 HRB
	P3015-						6.8	250	60	90	170	8	40 HRB
	P3025-	<0.2	3 to 6	<0.8	Balance	2	6.8	300	80	90	200	6	60 HRB
Nickel–copper steels[2]	P3034-	<0.3	1 to 3	1 to 3	Balance	2	6.4	240	70	85	170	3	35 HRB
	P3035-						6.8	270	90	90	200	4	45 HRB
	P3044-	0.3 to 0.6	1 to 3	1 to 3	Balance	2	6.4	300	100	85	260	1	55 HRB
	P3045-						6.8	360	120	90	300	2	70 HRB
	P3054-	<0.3	3 to 6	1 to 3	Balance	2	6.4	250	70	85	190	3	40 HRB
	P3055-						6.8	290	90	90	220	4	55 HRB
	P3064-	0.3 to 0.6	3 to 6	1 to 3	Balance	2	6.4	320	100	85	280	1	60 HRB
	P3065-						6.8	380	130	90	320	2	75 HRB

Notes: [1] Weldable.
[2] Heat treatable.

Table 23.12 NICKEL COPPER-MOLYBDENUM STEELS (AS SINTERED)

		Mandatory values						*Informative approximate values*						
		Chemical composition						*Mechanical and physical properties*						
Materials	*Grade*	*C combined* %	*Ni* %	*Cu* %	*Mo* %	*Fe* %	*Total other elements (max.)* %	*Density (min.)* g/cm³	*Ultimate Tensile strength (min.)* MPa	*Apparent hardness (min.) HV 5*	*Relative density* %	*Yield strength (0.2% offset)* MPa	*Elongation*[2] %	*Apparent hardness Rockwell*
Nickel-copper-molybdenum steels[1]	P3074-	<0.3	1 to 3	1 to 3	0.3 to 0.7	Balance	2	6.4	240	80	85	170	3	45 HRB
	P3075-							6.8	270	100	90	200	4	60 HRB
	P3076-							7.0	290	110	90	220	5	70 HRB
	P3084-	0.3 to 0.6	1 to 3	1 to 3	0.3 to 0.7	Balance	2	6.4	330	120	85	300	2	70 HRB
	P3085-							6.8	440	150	90	360	3	80 HRB
	P3086-							7.0	480	160	90	390	4	90 HRB
	P3094-	0.6 to 0.9	1 to 3	1 to 3	0.3 to 0.7	Balance	2	6.4	350	140	85	330	nm	75 HRB
	P3095-							6.8	460	170	90	400	nm	85 HRB
	P3104-	0.3 to 0.6	3 to 6	1 to 3	0.3 to 0.7	Balance	2	6.4	410	150	85	350	nm	80 HRB
	P3105-							6.8	600	180	90	450	1	85 HRB
	P3106-							7.0	680	200	90	520	2	90 HRB

[1] Heat treatable.
[2] nm = non-measurable.

Table 23.13 MECHANICAL PROPERTIES OF SINTERED AND HEAT TREATED STEELS

Plain carbon steels

Carbon content %	*Density* g/cm³	*Relative density class*	*Mechanical properties*							
			Hardness	*Ultimate tensile strength* MPa	*0.2% yield strength* MPa	*Elongation* %	*Impact strength** J	*Fatigue limit* MPa	*En* Gpa	*Poisson's ratio*
0.25–0.6	6.55	3	30 HRA	400	380	0.5	—	150	110	0.21
"	6.9	5	50 HRA	560	520	0.5	—	210	135	0.23
0.6–1.0	6.1	2	100 HRB	400	380	<0.5	—	150	90	0.20
"	6.55	3	25 HRC	500	480	<0.5	—	190	110	0.21
"	6.9	5	30 HRC	650	630	<0.5	—	250	135	0.23

Copper steels

Composition in weight %			*Density* g/cm³	*Relative density class*	*Mechanical properties*							
C	*Cu*	*Ni*			*Hardness HRC*	*Ultimate tensile strength* MPa	*0.2% yield strength* MPa	*Elongation* %	*Impact strength** J	*Fatigue limit* MPa	*En* Gpa	*Poisson's ratio*
0.25–0.6	1–3	—	6.5	3	30	580	550	<0.5	—	220	110	0.21
"	"	—	6.9	4	35	690	650	<0.5	—	260	130	0.23
0.6–1.0	1–3	—	6.1	2	25	380	360	<0.5	—	145	90	0.20
"	"	—	6.5	3	35	550	520	<0.5	—	210	110	0.21
"	"	—	6.9	4	45	690	650	<0.5	—	260	130	0.23

Nickel steels

0.25–0.6	—	2–4	6.6	3	32	670	550	0.5	7	270	115	0.22
"	—	"	7.1	5	42	910	550	0.5	15.5	360	145	0.24
"		"	7.3	6	45	1070	890	1.5	28	400	160	0.26
0.6–1.0		2–4	6.6	3	35	700	650	0.5	8	280	115	0.22
"		"	7.1	5	45	930	880	0.5	—	370	145	0.24
"		"	7.3	6	47	1100	1050	0.5	26	410	160	0.26
0.6–1.0		4–6	6.6	3	35	650	550	0.5	5	250	115	0.22
"		"	7.1	5	42	750	650	0.5	9	350	145	0.24

Copper nickel steels

Composition in weight %						*Mechanical properties*							
C	*Cu*	*Ni*	*Mo*	*Density* g/cm³	*Relative density class*	*Hardness HRC*	*Ultimate tensile strength* MPa	*0.2% yield strength* MPa	*Elongation* %	*Impact strength*[a] J	*Fatigue limit* MPa	*En* Gpa	*Poisson's ratio*
0.25–0.6	2–4	0.5–2	—	6.6	3	32	565	450	0.5	7.5	220	115	0.21
"	"	"	—	6.95	5	40	750	600	1	21	300	140	0.23
0.25–0.6	1–3	2–5	—	6.6	3	60 HRA500	500	—		190	110	0.21	0.21
"	"	"	—	6.95	5	65 HRA	620	—		—		130	0.23

Copper nickel–molybdenum steels

0.6–1.0	1.5	1.75	0.5	6.75	4	32	650	550	0.5	5	250	117	0.22
	"	"	"	7.1	5	42	900	750	1	9	350	145	0.24
0.25–0.6	1.5	4	0.5	6.75	4	24	715	560	0.5	—	285	117	0.22
"	"	"	"	7.1	5	38	980	770	1	—	390	145	0.24
0.6–1.0	1.5	4	0.5	6.75	4	30	790	660	0.5		320	117	0.22
"	"	"	"	7.1	5	40	1080	890	1		420	145	0.24

[a] IZOD impact test.

Table 23.14 COMPOSITIONS AND PROPERTIES OF STAINLESS STEEL POWDERS AND PRODUCTS

	Chemical compositions									*Physical properties*		*Green properties*			*Sintered properties*			
Alloy type	*C*	*Mn*	*Si*	*S*	*Cr*	*Ni*	*Mo*	*Fe*	*Cu*	*Apparent density* g/cm³	*Flow rate* s/50 g	*Compaction load* MPa	*Green density* g/cm³	*Green strength* MPa	*Sintered density* g/cm³	*Sintered strength* MPa	*Linear change* %	*Apparent hardness* HV30 kg
303 L stainless	0.02	0.15	0.75	0.20	17.56	12.80	—	Balance	—	2.8	32	695	6.48	5.17	6.71	911	−1.07	156
304 L stainless	0.02	0.18	0.66		18.90	10.50	—	Balance	—	2.8	31	695	6.72	8.14	6.83	815	−0.52	165
316 L stainless	0.02	0.18	0.83	—	17.00	12.75	2.15	Balance	—	2.6	33	695	6.83	7.31	6.90	1.092	−0.49	140
347 L stainless	0.2	0.18	0.67		18.20	10.80		Balance		2.6	32	695	6.67	7.24	6.81	946	−0.52	180
410 L stainless	0.02	0.20	0.76	—	13.00	—	—	Balance	—	2.7	32	695	6.59	12.41	6.76	1098	−0.78	163

Table 23.15 MECHANICAL PROPERTIES OF SINTERED COPPER ALLOYS

	Composition in weight %							*Mechanical properties*						
	Cu – Remainder													
Material	*Sn*	*Zn*	*Ni*	*Pb*	*Others*	*Density* g/cm³	*Relative density class*	*Hardness*	*Tensile strength* MPa	*0.2% yield strength* MPa	*Elongation* %	*Impact strength*[a] J	*En* Gpa	*Poisson's ratio*
	9–11	—		—	<2 (Fe <1)	5.8	1	20 HB	55	45	1	—	30	0.20
	"	—	—	—	"	6.6	2	25 HB	95	75	1	—	40	0.22
Bronze	"	—	—	—	"	7.0	2	30 HB	120	100	2.5	—	50	0.24
	"	—	—	—	"	7.6	4	45 HB	200	150	10	—	70	0.26
	"	—	—	—	"	8.2	7	50 HB	300	220	20	—	87	0.30
Brass	—	8.3–12	—	—	—	7.4	4	57 HRH	140	100	8	—	65	0.25
	—	"	—	—	—	7.8	5	70 HRH	185	130	12	—	80	0.28
Brass	—	27.8–31.5	—	—	—	7.4	4	76 HRH	215	150	20	—	70	0.25
	—	"	—	—	—	7.8	6	85 HRH	285	180	26	—	85	0.28
Leaded brass	—	7–11	—	1–2	—	7.4	3	46 HRH	120	90	14	—	65	0.25
	—	"	—	"	—	7.8	5	60 HRH	175	120	20	—	78	0.28
Leaded brass	—	20	—	1–2	—	7.4	4	50 HB	165	90	13	12	63	0.25
	—	"	—	"		7.8	5	60 HB	195	105	19	19	76	0.28
	—	"	—	"		8.2	7	—	220	120	23	25	90	0.30
Leaded brass	—	26.5–30.5	—	1–2	—	7.4	4	65 HRH	195	100	22	—	65	0.25
	—	"	—	"	—	7.8	5	76 HRH	235	130	27	—	77	0.28
Nickel silver	—	18	18	—		7.8	5	70 HB	200	120	10	12	84	0.28
	—	"	"	—		8.2	7	80 HB	250	140	12	14	100	0.30
Leaded nickel silver	—	13.2–20	16.5–19.5	1–1.8		7.8	5	70 HB	190	120	10	"	80	0.28
	—	"	"	"		8.2	7	80 HB	240	130	12	14	95	0.30

[1] Compressive yield strength.
[2] Unnotched Charpy impact test

between case and core is much more gradual. As would be expected, these effects are more marked the greater the amount of porosity (ss Figure 23.8). If the parts are first infiltrated (see Section 23.6) this effect largely disappears and a more nearly normal case is produced.

23.13 Steam Treatment

A process peculiar to sintered ferrous components is to heat them in superheated steam which produces a layer of magnetite, Fe_3O_4, on the surface including those of the surface-connected pores. This significantly increases the surface hardness and wear resistance, and to some extent the density, as can be seen in Table 23.16.

23.14 Wrought PM Materials

Substantial tonnages of wrought metals are made by PM. The products can be divided into three classes.

1. Metals that are difficult or impossible to produce in wrought form from ingot because of their inherent brittleness. Those of most commercial importance are tungsten, molybdenum, and the other refractory metals tantalum, niobium, and rhenium, as well as beryllium, chromium, and magnesium.
2. Metals containing a finely dispersed insoluble second phase. ODS materials and aluminium with a dispersion of aluminium carbide have been referred to in Section 23.3 under 'Mechanical alloying'. In such cases the purpose is to produce materials with better properties than are available in standard wrought products of the same nominal composition but without the dispersed phase. The metals aluminium, copper, nickel alloys especially superalloys, molybdenum, and other refractory metals strengthened in this way are in commercial production. Additionally copper and silver containing dispersed oxide(s) are used for make and break electrical contacts combining the excellent conductivity of these metals with marked resistance to welding.
3. Metals and alloys that present no great production difficulty starting from ingot, but which can be produced more economically from powder, generally because of the higher yield of finished material and/or reduction in the number of annealing and pickling steps. Superior properties can sometimes be claimed and result from the greater homogeneity and freedom from pipe defects. Of importance commercially are austenitic stainless steels and superalloys.

23.14.1 Refractory metals

Tungsten wire was one of the first PM products to be made on a large scale, the use being filaments for incandescent electric light bulbs, for which purpose it is still made. In order to induce in the wire a particular elongated microstructure which increases remarkably the life of the filament, a

Table 23.16 EFFECTS OF STEAM TREATING ON DENSITY AND HARDNESS OF FERROUS PM MATERIALS

	Density, g/cm³		Apparent hardness	
Material	Sintered	Steam treated	Sintered	Steam treated
Plain iron	5.8	6.2	7 HRF	75 HRB
	6.2	6.4	32 HRF	61 HRB
	6.5	6.6	45 HRF	51 HRB
Carbon steel	5.8	6.1	44 HRB	100 HRB
	6.2	6.4	58 HRB	98 HRB
	6.5	6.6	60 HRB	97 HRB
6–8% Ni steel	5.7	6.0	14 HRB	73 HRB
	6.35	6.5	49 HRB	78 HRB
	6.6	6.6	58 HRB	77 HRB
6–8% Ni, 2% Cu steel	5.7	6.0	52 HRB	97 HRB
	6.3	6.4	72 HRB	94 HRB
	6.6	6.6	79 HRB	93 HRB

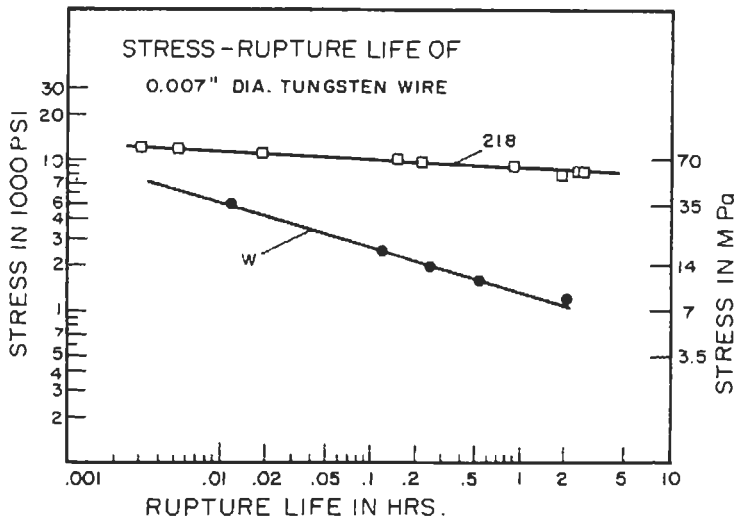


Figure 23.9 *Stress dependence of rupture life in hours of 0.007" (178 μm) tungsten wire at 3000 K. W is pure tungsten wire, 218 is doped tungsten wire*

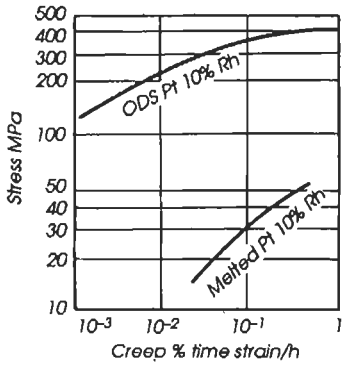


Figure 23.10 *Creep strength of ODS Pr/10% Rh*

small percentage of thorium oxide was included. It is to tungsten doped in this way that the properties shown in Figure 23.9 refer.

Molybdenum is used extensively in high-temperature furnaces as heating elements, radiation shields, and structural components. The high-temperature strength can be increased by ODS. ODS platinum/rhodium used for handling molten glass has much improved creep strength as is shown in Figure 23.10.

23.14.2 Superalloys

This family of alloys is used for load-bearing applications at elevated temperatures, and is especially relevant to turbine discs and blades for aircraft engines. For manufacture by PM, spherical powders produced either by gas (usually argon) atomization or centrifugal atomization are used. The attractions of the PM route are that it is possible to achieve a fine homogeneous structure free from pipe-related defects and segregation, and also a better yield of usable material. Table 23.17 lists some relevant properties of one well known alloy.

Table 23.17 MECHANICAL PROPERTIES OF NIMONIC ALLOY AP1 DISCS HIPPED AND FORGED (Inco Alloys International)

		Tensile properties						Stress rupture 760 MPa at 705°C			Low fatigue at 600°C	
								Plane		Notch		
Disc size	Solution treatment	T_{test} °C	Yield strength (0.2% offset) MPa	Ultimate tensile strength MPa	Elongation %	Reduction of area %	Notched tensile strength MPa	Life h	Elongation %	Life h	Stress MPa	Life cycles
380 mm dia.	4 h/1110°C/AC	650	906	1316	30.4	30.5	1627	51	11.5	699	1080	125 200
											+1100	21 510
											+1120	1 390
380 mm dia.	4 h/1160°C/AC	650	902	1348	25.9	27.0	1599	63	19.5	424	1080	40 0007
280 mm dia.	4 h/1080°C/QQ	650	961	1325	26.8	28.7	1701	109	7.6	814	1080	54 063
280 mm dia.	4 h/1160°C/OQ	650	977	1370	25.9	23.9	1678	107	8.9	252	1080	123 200
											+1100	20 000
											+1120	20 000
											+1140	4 430
200 mm dia.	4 h/1080°C/OQ	R.T.	991	1369	18.5	20.0						
200 mm dia.	4 h/1160°C/OQ	R.T.	1045	1451	22.8	35.4						

Aged 24 h 650°C air cool and 8 h air cool; R.T.: Room temperature, AC: air cool, OQ: oil quench.

Composition of Nimonic alloy AP1 (wt percent.)

C	Al	Co	Cr	Mo	Ti	Zr	B	Ni
0.02	4.0	17.0	14.8	5.0	3.5	0.04	0.02	bal

Superalloys owe their good strength properties to precipitation hardening by a titanium–aluminium compound, but as the temperature rises, this compound begins to go into solution and loses its effect. This puts a ceiling on the working temperture. The mechanical alloying process to produce a fine dispersion of a ceramic material—yttria is favoured—that is virtually insoluble in the metal matrix, significantly increasing the temperature at which useful strength is retained. A list of ODS superalloy compositions is given in Table 23.18, and Figure 23.11 shows the improved performance of one of these alloys compared with that of a similar composition made conventionally.

23.14.3 Copper

One of the main users of copper is the electrical industry where conductivity is the primary consideration. Increasingly, power plant is required to operate at temperatures well above ambient where pure copper recrystallizes and becomes very soft. Increasing the strength and recrystallization temperature by alloying drastically reduces the conductivity. The inclusion in pure copper of a small percentage of finely dispersed aluminium oxide provides significantly better elevated temperature strength with only a small reduction in conductivity. An atomized powder of a dilute aluminium copper alloy is internally oxidized to give a very fine Al_2O_3 particles, the powder being then processed by compaction, sintering, and working. The improved strength at room temperatures enables smaller sections to be used in, for example, miniaturized systems. Figure 23.12 gives some results for a range of alumina contents.

23.14.4 Lead

This is another soft metal whose strength can be increased by a dispersed oxide phase. In this case lead oxide is used. The chief application is to chemical plant especially for handling sulphuric acid.

Table 23.18 NOMINAL COMPOSITIONS (WT%) OF MECHANICALLY ALLOYED OXIDE DISPERSION STRENGTHENED SUPERALLOYS

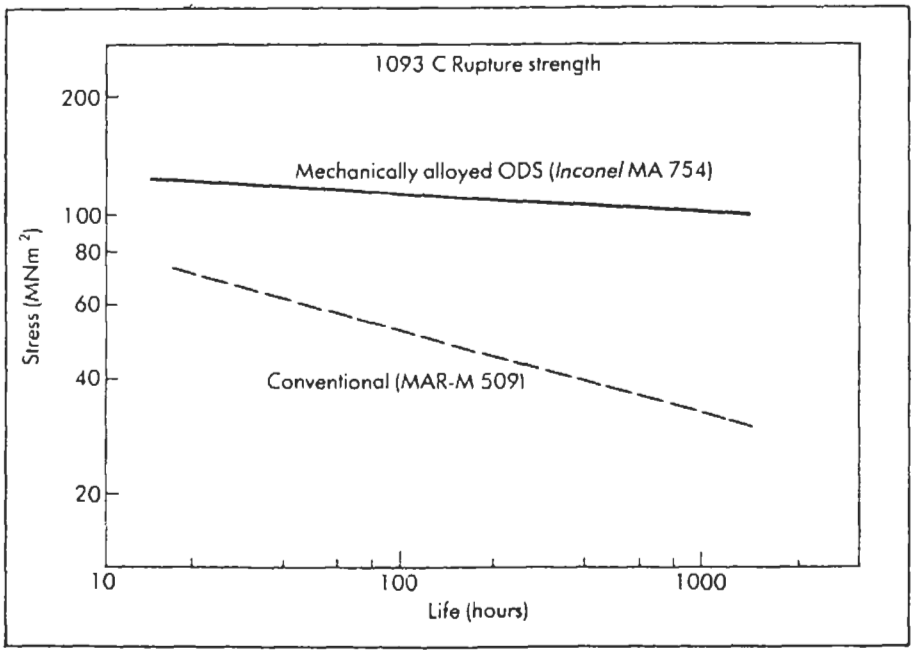
	Ni	Fe	Cr	Al	Ti	C	Y_2O_3	Mo	W	Ta	B	Zr
INCOLOY* alloy MA 956		Bal	20	4.5	0.5	0.05	0.5					
INCOLOY alloy MA 957		Bal	14		1.0	0.05	0.25	0.3				
INCONEL* alloy MA 954	Bal	1.0	20	0.3	0.5	0.05	0.6					
INCONEL alloy MA 758	Bal	1.0	30	0.3	0.5	0.05	0.6					
INCONEL alloy MA 6000	Bal		15	4.5	2.5	0.05	1.1	2.0	4.0	2.0	0.01	0.15
INCONEL alloy MA 760	Bal		20	6.0		0.05	0.95	2.0	3.5		0.01	0.15

*INCOLOY and INCONEL are trademarks of the Inco family of companies.

Iron–chromium alloys: INCOLOY alloy MA 956 sheet, plate, bar, spinnings, rings and forgings have applications in the hot sections of gas turbines and diesel engines where the resistance of the alloy to creep, oxidation and sulphidation allow higher metal temperatures and longer component life. The alloy is being used to replace molybdenum in high-temperature vacuum furnaces for fixtures and heat-treatment trays. INCOLOY alloy MA 957 is intended for nuclear power applications, especially fuel cladding in liquid metal cooled reactors. Compared with 316 type stainless steel it has higher strength at 700°C and considerable resistance to irradiation damage.

Nickel–chromium alloys: INCONEL alloy MA 754 is used for brazed nozzle guide vane and band assemblies in advanced military aero engines. The principal advantages of the alloy for these applications are thermal fatigue resistance, long term creep strength and a high melting point. INCONEL alloy MA 758 is highly resistant to attack by molten glass and is used in spinnerettes for the production of fibre glass. The parts are formed by hot spinning plate.

Gamma prime ODS alloys: The immediate applications for INCONEL alloy MA 6000 are for first- and second-stage turbine vanes and blades machined from solid bar. Forced airfoil components have also been developed. The characteristics of INCONEL alloy MA 6000 allow blade cooling to be reduced or eliminated as the metal temperature can be increased by 100 K or more in engines where the stresses are medium or low. INCONEL alloy MA 760 is an industrial gas turbine derivative of INCONEL alloy MA 6000 having greater resistance to corrosion and oxidation. Initial applications are for machined vanes and blades but forged components are under development.



(Inco Alloys International)

Figure 23.11 *Properties of mechanically alloyed Income (Inconel is a trademark of Inco Alloys International) compared with a conventional superalloy*

Composition of Inconel *alloy MA* 754:

Fe	Al	Cr	C	Y_2O_3	Ti	Ni
1.0	0.3	20	0.05	0.6	0.5	bal.

23.14.5 Aluminium

Section 23.3.1 referred to the mechanical alloying of Al with graphite to produce powder containing a dispersion of aluminium carbide. This powder containing a dispersion of aluminium carbide. This powder compacted into billets and extruded gives a product with much improved strength at elevated temperatures (see Figure 23.13). This may have applications in aircraft where weight saving is of significant value.

23.15 Spray Forming

This process is not powder metallurgy in the strict sense of the term in so far as the metal is at no stage in the form of powder. However, for reasons that will be apparent the PM world has adopted it. The process involves gas atomization of a liquid metal, but instead of allowing the droplets to solify as powder, the spray is caused to impinge on a solid surface where the droplets are collected as a semi-solid layer which solidifies as a layer of dense metal. This layer may be built up to any desired thickness, and by suitable choice of design of the original target, the angle of the spray, and other parameters, near-net shapes can be produced. For example if the target is a cylinder rotating horizontally and capable of being moved in a controlled manner in the axial direction, a tube of dense deposited metal is formed. The deposit has all the advantages of dense metal produced from powder, i.e. complete absence of macro-segregation and pipe-related defects. A further merit of the process is that by injecting fine refractory powder particles, i.e. by entraining them in the atomizing gas stream, ODS material can be deposited.

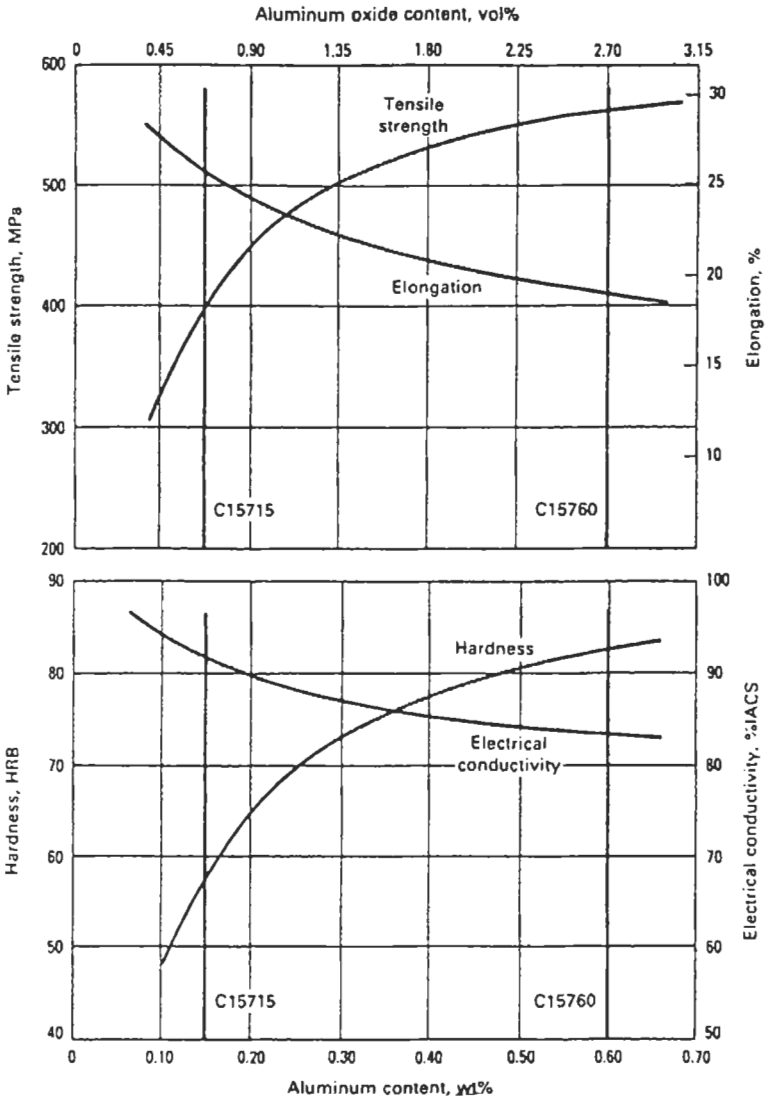


Figure 23.12 *Properties of dispersion-strengthened copper (C15715 and C15760 are compositions made by SCM Metal Products)*

23.16 Injection Moulding

Commonly referred to as MIM (metal injection moulding), this proprietary process consists of mixing fine $\leqslant 20\,\mu m$ metal powder with a thermosetting organic material to form a plastic mass that can be injected under pressure into a mould to form the equivalent of a compact. The part is then carefully treated by solvents and/or heat to remove the binder and then at a higher temperature eventually to sinter the metal. Shrinkage of the order of 10% linear occurs but this can be predicted accurately and parts with very close dimensional tolerances and of quite complex shape can be made. It is an expensive process but the advantages in eliminating expensive machining operations make it viable for a number of applications.

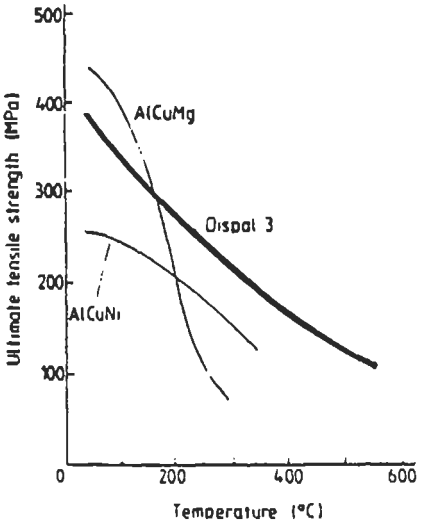


Figure 23.13 *Strength/temperature relationship of aluminium with a dispersion of Al_4C_3 produced by mechanical alloying compared with ingot-based high strength alloys. Dispal is a trademark of Sintermetallwerk Krebsöge*

23.17 Hardmetals and related Hard Metals

This family of PM materials consists of fine, hard, and usually brittle particles bonded with a relatively soft and tough binder phase which is normally metallic. The hard particles are generally between 1 and 5 μm, but even finer grades with particles below 1 μm are now being made. The original hard phase was tungsten monocarbide (WC) and the preferred binder phase was cobalt. The name *cemented carbide* was, and to a large extent still is, used to describe these materials, but the official name is now *hardmetal*. Carbides other than that of tungsten were later added, e.g. those of tantalum, niobium, and titanium, and binder metals other than cobalt have been used, but the WC/Co-based compositions still have the lion's share of the market. More recently, products have been developed in which the hard phase is not carbide, but nitride, boride, carbo-nitride, oxide, or combinations of these. Such materials may not strictly be called hardmetals since hardmetal has been defined in ISO standard 3252 as 'sintered material characterized by high strength and wear-resistance comprising carbides of refractory metals as the main component together with a metallic binder phase'.

Uses

Hardmetals were originally developed as a substitute for diamond as wire drawing dies for tungsten, and they are still used for that purpose, but the largest single use today is as cutting tools. It is for this application that the non-carbide alloys have been developed, but no cost effective substitute has been found for the WC/Co hardmetal where straightforward wear resistance is the primary requirement, and this includes cutting tools for non-ferrous metals and non-metallic materials. Other such cases are wire drawing dies, dies for the compaction of metal powders for the manufacture of PM parts, rolls for metal rolling mills, and other large abrasion-resistant parts.

Manufacture

The process for the production of hardmetal is a classic example of liquid phase sintering: a mixture of WC and cobalt powders is pressed and sintered at a temperature above the melting point of cobalt. However, to get good results special procedures in the preparation of the powder mix are necessary. The incredients are wet milled together in order to coat each carbide particle with cobalt, and to facilitate this, the cobalt powder must be extremely fine. It is well known that very fine powders do not flow readily, if at all, and to overcome this problem the WC/Co mixture is 'granulated', by which is meant the production of agglomerates. A favoured method of granulation

is the spray drying of a slurry of the powder with a liquid containing also a pressing lubricant. During sintering, the compact shrinks by as much as 50 vol% to become nearly 100% dense. The sintering temperature used in practice varies with the composition, being lowest (1400°C) when the cobalt content is high, and rising to 1600°C) or higher with compositions having high proportions of the carbides of Ti, Ta, and/or Nb and low cobalt contents. In cases where it is not posible to get close to the required shape by direct pressing and sintering, the compact may be pre-sintered at a lower temperature so as to remove the lubricant and provide sufficient strength for handling. In this state, the object can be machined using tools of bonded diamond or other hard material.

Although it is usual to refer to the binder phase as being cobalt there is some mutual solubility between it and the carbide, and great care is needed to ensure that the carbon balance is maintained such that neither the brittle W/Co (eta) phase nor free graphite is formed. The toughness is affected also by the size of the carbide particles; the finer they are the harder but less shock-resistant is the final product, However, grades with carbide particle size well below 1 μm are reported to combine high hardness with toughness.

Hot Iso-static Pressing

Although the porosity of conventionally produced hardmetal is normally low, porosity can be completely eliminated by hot iso-static pressing (HIPping). Toughness is, thereby considerably increased and the possibility of the rejection of large and expensive components at a late stage of grinding or polishing no longer presents a problem. HIPping is now routinely applied to a large number of hardmetal parts including indexable cutting tool tips that are a major product. Recently it has been found possible to combine HIPping with the sintering stage. The parts are sintered in vacuum to a density such that the porosity is sealed, and then high pressure gas, usually argon, is introduced into the furnace. The pressure required for full densification is lower than that needed for the HIPping of already sintered parts, and the new process, referred to as Sinter-HIP or Pressure Assisted Sintering is rapidly replacing the original two-stage process of vacuum sintering followed by HIPping in a separate furnace, at least for cutting tool tips.

Compositions

Straightforward WC/Co hardmetal appears to be the most cost-effective material for many applications where wear resistance is the primary requirement, including the machining of non-ferrous metals. Additions of e.g. TaC improve the already good wear resistance, perhaps by acting as grain growth inhibitors, and are especially valuable in applications involving high temperatures. When the use is the machining of ferrous materials at high speeds, the situation is different. In addition to abrasive wear, reaction between the carbide particles and the steel results in what is known as crater wear. The substitution of more stable carbides such as those of Ta, Nb, Ti, and Hf for some or all of the WC considerably improves the cratering resistance. Wear resistance is, as would be expected, markedly influenced by the amount of binder phase as shown in Figure 23.14, but reduction in the cobalt content also makes the alloy more brittle, so a compromise between toughness and wear resistance is necessary.

Table 23.19 gives compositions and properties of one manufacturer's range. Table 23.20 lists the ISI classification of carbides according to use.

Alternative Binders

Because of the high price of cobalt and the perceived instability of the countries that produce the bulk of it, continuing efforts have been made to find alternatives. Ni, Fe, and Ni/Mo have been used successfully in certain applications, and a recent entry into the field is Ni/Cr which now appears in some commercial grades. One grade is based on TiC with MoC and a Ni/Mo binder. Good results have been reported also with a superalloy binder which combines conspicuous high-temperature strength with toughness. Useful resuls have been reported also with a nickel binder containing ruthenium, but this member of the platinum group is, of course, relatively very costly.

Coatings

For tools for the machining of steels the most dramatic improvement has been the development of surface coatings. An ideal tool material from the cutting point of view would be a pure, very

Table 23.19 COMPOSITION AND PROPERTIES OF TIZIT GRADES OF HARD METAL

ISO codes	*TIZIT grades*	*Chemical composition–weight %*					Average grain size μm	*Transverse rupture strength* MPa	*Density* g/cm³
		WC	TiC	Ta (Nb) C	Co	Ni/Cr			
P05	S05T	60.5	22	11	6.5	—	2–3	1400	10.0
P10	S10T	69	16	8	7	—	2–3	1650	11.3
P20–25	S22T	71.5	9	11	8.5	—	2–3	1800	12.4
P20–P30	S26T	69.5	6.5	14	10	—	2–3	1900	12.7
P30–P40	S36T	76.5	4	7.5	12	—	2–3	2200	13.1
P40	S40T	77	4	8	11	—	3	2400	13.3
M10	U10T	83.5	5	5.5	6	—	1–2	1800	13.5
M10–M20 K10–K20	U16T	84	7.5	1	7.5	—	1	1800	12.9
M15	U17T	86	2.5	5.5	6	—	3	1950	14.0
M20	U20T	77	4	10	9	—	3	2050	13.3
K01–K05	H03T	96.7	—	0.3	3	—	1	1600	15.3
K05	H05T	87.5	1.5	6	5	—	1	1800	14.5
K10	H10T	94.2	—	0.3	5.5	—	1	1900	14.8
K10–K20	H16T	93.7	—	0.3	6	—	1–2	1950	14.9
K20	H20T	93.2	0.2	0.6	6	—	2	2000	14.7
K20–K30	H25T	90.2	—	0.3	9.5	—	1	2100	14.7
K30	H30T	90.2	0.2	0.6	9	—	2	2200	14.6
K40	H40T	87.2	0.2	0.6	12	—	2	2550	14.3
K50	H50T	84.2	0.2	0.6	15	—	2	2800	14.0
	H60T	80	—	—	20	—	3	3000	13.5
	H70T	76	—	—	24	—	3	2900	13.2
	H80T	72	—	—	28	—	3	2800	12.8
	B10T	94	—	—	6	—	2–3	2050	14.9
	B30T	91	—	—	9	—	3–4	2500	14.6
	B40T	88	—	—	12	—	3–4	2550	14.2
	B50T	85	—	—	15	—	3–4	2600	14.0
	TCR10	94	—	—	—	6	1–2	2000	14.8
	TCR30	91	—	—	—	9	2	2300	14.4
K05–K20	Sr16*	86	2.5	5.5	6	—	3	—	—
P05–P25 K05–K20	Sr17*	86	2.5	5.5	6	—	3	—	—
P05–P20 K05–K20	Gm 15**	83.5	5	5.5	6	—	1–2	—	—
P15–P30 K10–K20	Gm 25**	77	4	10	9	—	3	—	—
P15–P30 K10–K20	Gm 26***	77	4	10	9	—	3	—	—
P25–P40	Gm 35**	76.5	4	7.5	12	—	2–3	—	—
P25–P40	Gm 36***	76.5	4	7.5	12	—	2–3	—	—
P05–P25	Gm 176***	86	2.5	5.5	6	—	3	—	—
P35–P45	Gm 306***	91	—	—	9	—	3–4	—	—

* Coating/thickness 8 μm.
** Coating/thickness TiC, Ti(C, N), TiN 10–12 μm.
*** Coating/thickness TiC, Ti(C, N), TiN 5 μm.

Hardness HV30	*Compressive strength* GPa	*Young's modulus of elasticity* GPa	*Poisson's ratio*	*Coercive force* kA/m	*Electrical resistivity* μΩ cm	*Thermal conductivity* (20°C) W/mK	*Coefficient of thermal expansion* (20–400°C) 10^{-6}/K
1705	5.3	490	0.22	11.94	91	25	7
1675	5.3	530	0.22	11.94	58	30	6
1575	5.2	540	0.22	11.94	37	40	6
1555	5.1	550	0.22	13.13	30	50	6
1390	5.0	560	0.22	11.14	25	60	5.5
1420	4.9	540	0.22	11.94	24	60	6
1685	5.7	620	0.22	14.92	24	60	5.5
1730	5.7	600	0.22	19.89	26	50	5.5
1575	5.3	590	0.22	12.73	25	60	5.5
1460	5.1	550	0.22	10.5	28	60	5.5
1850	6.1	660	0.22	24	20	100	5
1830	6.1	650	0.22	19.5	23	100	5
1750	6.0	650	0.22	18.70	20	100	5
1675	5.8	640	0.22	17.11	20	100	5
1615	5.7	640	0.22	15.12	20	100	5
1545	5.5	630	0.22	14.72	18	90	5
1470	5.4	620	0.22	12.33	18	90	5
1340	5.0	600	0.22	10.74	17	90	5.5
1225	4.5	570	0.23	9.55	17	80	6
1030	3.8	520	0.24	7.00	17	70	6
920	3.5	500	0.24	5.81	16	60	6.5
855	3.2	480	0.24	5.25	16	60	6.5
1500	5.5	650	0.22	11.95	19	100	5
1215	4.2	630	0.22	7.3	19	90	5
1115	4.0	580	0.22	6.5	19	80	5.5
990	3.8	560	0.23	6.0	17	80	6
1500	5.5	630	0.19	—	—	70	5
1400	5.0	600	0.21	—	—	61	4.8
Hardness of coating > 2000 V							

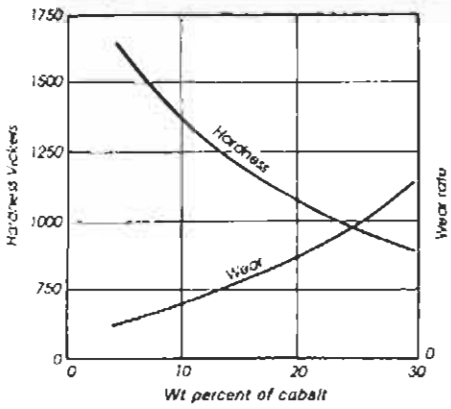


Figure 23.14 *Relationship between cobalt content, hardness and wear of WC/Co hard metal*

Table 23.20 ISO CLASSIFICATION OF CARBIDES ACCORDING TO USE

Main groups of chip removal			*Groups of application*			*Direction of increase in characteristic*	
Symbol	*Broad categories of material to be machined*	*Distinguishing colours*	*Designation*	*Material to be machined*	*Use and working conditions*	*of cut*	*of carbide*
P	Ferrous metals with long chips	BLUE	P 01	Steel, steel castings	Finish turning and boring, high cutting speeds, small chip section, accuracy of dimensions and fine finish, vibration-free operation	Increasing speed ↑	Wear resistance ↑
			P 10	Steel, steel castings	Turning, copying, threading and milling, high cutting speeds, small or medium chip sections	Increasing feed ↓	Toughness ↓
			P 20	Steel, steel castings Malleable cast iron with long chips	Turning, copying, milling, medium cutting speeds and chip sections, planing with small chip sections		
			P 30	Steel, steel castings Malleable cast iron with long chips	Turning, milling, planing, medium or low cutting speeds, medium or large chip sections, and machining in unfavourable conditions*		
			P 40	Steel Steel castings with sand inclusion and cavities	Turning, planing, slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavourable conditions* and work on automatic machines		
			P 50	Steel Steel castings of medium or low tensile strength, with sand inclusion and cavities	For operations demanding very tough carbides: turning, planning slotting, low cutting speeds, large chip sections, with the possibility of large cutting angles for machining in unfavourable conditions* and work on automatic machines		

M	Ferrous metals with long or short chips and non-ferrous metals	YELLOW	M 10	Steel, steel castings, manganese steel Grey cast iron, alloy cast iron	Turning, medium or high cutting speeds. Small or medium chip sections	↑ Increasing speed ↓ Increasing feed → Wear resistance ← Toughness
			M 20	Steel, steel castings, austenitic or manganese steel, grey cast iron	Turning, milling. Medium cutting speeds and chip sections	
			M 30	Steel, steel castings, austenitic steel, grey cast iron, high temperature resistant alloys	Turning, milling, planing. Medium cutting speeds, medium or large chip sections	
			M 40	Mild free cutting steel, low tensile steel Non-ferrous metals and light alloys	Turning, parting off, particularly on automatic machines	
K	Ferrous metals with short chips non-ferrous metals and non-metallic materials	RED	K 01	Very hard grey cast iron, chilled castings of over 85 Shore, high silicon aluminium alloys, hardened steel, highly abrasive plastics, hard cardboard, ceramics	Turning, finish turning, boring, milling, scraping	↑ Increasing speed ↓ Increasing feed → Wear resistance ← Toughness
			K 10	Grey cast iron over 220 Brinell, malleable cast iron with short chips, hardened steel, silicon aluminium alloys, copper alloys, plastics, glass, hard rubber, hard cardboard, porcelain, stone.	Turning, milling, drilling, boring, broaching, scraping	
			K 20	Grey cast iron up to 220 Brinell, non-ferrous metals: copper, brass, aluminium	Turning, milling, planing, boring, broaching, demanding very tough carbide	
			K 30	Low hardness grey cast iron, low tensile steel, compressed wood	Turning, milling, planing, slotting, for machining in unfavourable conditions* and with the possibility of large cutting angles	
			K 40	Soft wood or hard wood Non-ferrous metals	Turning, milling, planing, slotting, for machining in unfavourable conditions* and with the possibility of large cutting angles	

* Raw material or components in shapes which are awkward to machine: casting or forging skins, variable hardness etc., variable depth of cut, interrupted cut, work subject to vibrations.

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hard, and stable compound such as one of the more stable carbides, nitrides, or oxides, were it not for the fact that they are far too brittle. However, if they are applied as a very thin layer to a sufficiently strong and tough substrate, an approximation to the best of both worlds is possible. Such coatings can be applied successfully by chemical vapour deposition (CVD) or physical vapour deposition (PVD). Titanium nitride, TiN, is widely used and gives the tool a striking gold colour. An essential requirement, of course, is that the coating adheres firmly to the substrate and this is facilitated by using multiple coatings only a few micrometres thick. Another factor in the equation is the possibility of reaction between the coating and the substrate and between the coating and the steel workpiece. In addition to nitrides, carbides, carbo-nitrides, borides, and oxides—especially alumina—are used, and as many as ten layers are applied, so the permutations are manifold. Recent additions to the range of coatings are cubic boron nitride (CBN) and diamond, but the latter is not suitable for the high-speed cutting of steel because it reacts with the steel at the high temperatures that are reached. The importance of matching the tool to the application should be emphasized.

Tool Life

In cutting applications much is made of the improved tool life of modern throw-away inserts achieved by careful design of substrate and coating, but a more important factor from the economic point of view is the improved cutting speed that is made possible. The cost of the tool insert is a small part only of the total machining cost, and if the cutting rate can be doubled and the tool life halved in consequence, the overall efficiency may well be much greater than that of prolonging the life of the tool.

Acknowledgements

Associazione Industriali Metallurgici Meccanici Affini (AMMA)	Tables 23.9, 23.13 and 23.15
American Society for Metals (ASM)	Figures 23.3 and 23.12
British Powder Metals Federation (BPMF) and Powder Metal Industries Federation (MPIF)	Tables 23.10, 23.11 and 23.12
BSA Metal Powders	Table 23.14
gkm Bound Brook	Table 23.8
Hoeganaes Corporation	Table 23.7
Hganäs AB	Table 23.6
Inco Alloys International	Tables 23,17 and 23,18
Makin Metal Powders	Tables 23.4 and 23.5
Metal Powder Industries Federation	Tables 23.2 and 23.16, and Figure 23.9
Metallnormencentralen	Table 23.3, and Figure 23.1
Metallwerk Plansee	Tables 23.19 (properties of hardmetals)

24 Lubricants

24.1 Introduction

Lubricants minimize friction and wear in rubbing contacts. They may also prevent rusting and with liquid lubricants remove heat. Lubricants may be solid, such as graphite, molybdenum disulphide, polytetrafluoroethylene and talc; or gaseous, commonly air; but the principal lubricants are liquids such as mineral oil, or the semi-solid greases formed from liquids by the use of thickening agents.

24.1.1 Hydrodynamic lubrication

A viscous fluid interposed between two solid surfaces moving in very close proximity to one another becomes pressurized and holds those surfaces apart, often against considerable loads, provided there is a position of closest approach of the surfaces towards which the net flow of fluid is directed. The effect is called hydrodynamic lubrication.

The condition that the net lubricant flow must be towards the position of closest approach of the surfaces is fulfilled in journal bearings by the journal automatically assuming an eccentric position in the bearing. It is not fulfilled if the surfaces are absolutely parallel to one another, but if the bearing surface can tilt appropriately as in the Michel tilting pad bearing, considerable loads can be carried. The amount of tilt required is almost imperceptible: approximately 1 in 10 000. If a position of closest approach can be developed by slight elastic or thermal distortion considerable fluid pressures can be developed between apparently parallel surface.

For very high pressures over tiny contact areas films as thin as 10 nm have been measured.

24.2 Friction, wear and boundary lubrication

In hydrodynamic lubrication friction is purely viscous and is directly dependent on the area of the film, the rate of shear and the viscosity of the lubricant. Coefficients of friction are as low as 0.001–0.003 and wear is negligible. When the speed of sliding and the oil viscosity are insufficient for the viscous film to carry the load, contact occurs between asperities on the opposing surfaces. Friction then rises and wear ensues. Where viscous effects are absent or negligible, lubrication is independent of the nominal area of contact and is said to be of boundary type. Where boundary and viscous effects occur together, the conditions are said to be those of 'mixed' lubrication.

When sliding speeds are very low indeed a 'stick-slip' or jerky motion arises due in part to the elastic response of the drive and in part to the coefficient of static friction exceeding the coefficient of dynamic friction. This undesirable effect can be suppressed by the use of special lubricants containing fatty acids, acid phosphates, or similar materials able to react with the metal surfaces to produce soft, easily-sheared layers of soap which considerably reduce the coefficient of static friction.

For moderate sliding speed and load, boundary lubrication can exist with only the oxide film being worn away and replaced at a tolerable rate of wear. Under these conditions lubricants which produce low friction do not necessarily produce low wear. For most machine bearings, boundary lubrication is inadequate, since the oxide film wears away very rapidly and direct metal to metal contact occurs. The surface asperities weld together momentarily and are broken apart again to produce wear debris largely composed of metallic particles. This is called adhesive wear, or scuffing.

Boundary lubrication is the most important mode in the chipless-forming type of metal working operation since the local pressures have to be high enough to exceed the yield strength of the metal. In such operations the surface area of the workpiece is being enlarged and new, easily-weldable areas are being created. For severe operations, therefore, solid lubricants are used which can resist high pressures and are capable of extension to cover the new areas. Examples of such lubricants are waxes, graphite, molybdenum disulphide, talc, whiting and pastes of dry soap and fats. For more severe operations such as tube and bar drawing thick layers of lubricants may be built up before the operation by, for example, phosphating, baking on a coating lime, treating with special inorganic salts, or by coating with soft metals such as lead.

24.3 Characteristics of lubricating oils

24.3.1 Viscosity

Viscosity is probably the most important property of a lubricating oil or grease. For most fluids in laminar flow there is a linear relationship between the shear stress and the rate of shear. The constant of proportionality is the viscosity or, more specifically, the dynamic viscosity to distinguish it from the kinematic viscosity which is given by the ratio of viscosity to density.

Dynamic viscosity may be defined as the shear stress necessary to move a flat surface at unit speed over a parallel surface unit distance apart when the intervening space is filled with the fluid. In SI units, dynamic viscosity is expressed in $N\,s\,m^{-2}$, but the centipoise or $nN\,s\,m^{-2}$ is at present commonly used. Direct measurements are relatively few. Usually dynamic viscosities are derived from measurement of density and kinematic viscosity, which is easily measured in calibrated glass capillary tubes using gravity flow. The units of kinematic viscosity are $m^2\,s^{-1}$ but centistokes ($1 \times 10^{-6}\,m^2\,s^{-1}$) are most commonly used. Obsolescent units such as Redwood and Saybolt seconds and Engler degrees derived originally from short efflux tube instruments are still to be found, but nowadays they are derived from measurement of kinematic viscosity with which they have almost linear relationships.

With increase of temperature, the viscosity of gases rises while that of liquids falls. A moderately viscous mineral oil falls from $1\,N\,s\,m^{-2}$ at 5°C to $0.01\,N\,s\,m^{-2}$ at 100°C. This property is commonly expressed as the Kinematic Viscosity Index (KVI) measured over the range 37.8–98.9°C (100–210°F) and expressed in values usually ranging between 0 and 100. However, a more rational Dynamic Viscosity Index, which may be measured over any convenient range, has been proposed. Oils with a KVI of 35 and below are known as Low Viscosity Index (LVI) oils, those between 35 and 80 are Medium Viscosity Index (MVI) oils, those between 80 and 110 are High Viscosity Index (HVI) oils and those over about 110 are Very High Viscosity Index (VHVI) oils.

With minerals oils and oils of similar molecular weight, viscosity is independent of the rate of shear, exept possibly under very high pressures. Shear rates in elastohydrodynamic lubrication (or EHL) are said to be 'Newtonian'. Oils of very high molecular weight, such as silicones, exhibit a reduction in viscosity at quite moderate rates of shear and are said to be 'non-Newtonian'. While such loss in viscosity may be only temporary, there may also be permanent loss due to mechanical breakdown of very high molecular weight polymer molecules.

The lubricant viscosity usable in practice depends on the type of machine involved. Low viscosity oils are used for high speeds and high viscosities for low speeds. Very approximately $3\,N\,s\,m^{-2}$ is the maximum viscosity at which machines can be started up, while 0.002 is the minimum for maintaining hydrodynamic lubrication under running conditions.

24.3.2 Boundary lubrication properties

This property of a lubricant is essentially its ability to produce on one or both of the rubbing surfaces a layer of adequate thickness of coherent and adherent, low shear strength material which will minimize metal-to-metal contact and reduce friction. Lubricants exemplifying this property under very mild, slow speed conditions are the fatty acids which produce soap layers on metals with active oxide surfaces, such as copper.

Under such mild conditions the property is often known as 'lubricity'. Under more severe conditions of load, speed and temperature, the property is known as 'Extreme Pressure' or 'EP'. As

an example, free sulphur is added to cutting oils to prevent excessive tool wear with tough steels.

24.3.3 Chemical stability

Lubricants are usually required to have an effective life of some hundreds or thousands of hours during which its necessary properties are sensibly unaltered. They may, however, change in whole or part by thermal decomposition, oxidation or by hydrolysis. Thermal decomposition followed by polymerization results in the formation of materials of very high molecular weight, especially insoluble coke-like substances, as well as low molecular weight materials including gases. The viscosity and flash point of the lubricant therefore generally drops. Similar materials are also formed during oxidation, but in addition highly oxygenated species including lacquers and organic acids are formed and the viscosity generally increases. This viscosity increase, the amount of insoluble material and the increase in organic acidity, are conveniently used as expressions of the degree of oxidation. Lubricants based on esters and lubricants containing esters or salts as components, e.g. as additives, are subject to hydrolysis and here again acidity, perhaps with a corrosion test for a sensitive metal such as lead, are used as criteria of stability.

Water-containing lubricants require particularly clean working conditions as contamination may lead to bacterial attack and thus to unpleasant odour, corrosion, and reduced effectiveness. Systems should be prepared and regularly cleaned by flushing with 5% solutions of caustic soda, detergent solutions or both. Biostats or biocides may also be helpful.

24.3.4 Physical properties

The thermal capacity of an oil is particularly important as in many cases the flow of oil is used to remove heat. Thermal capacity varies from around $2000\,J kg^{-1}K$ for mineral oils to around 1 500 for silicones and triaryl phosphate esters, which compare with $4\,200\,J kg^{-1}K$ for water.

In general, lubricants must not evaporate rapidly at the highest temperatures of usage. At well above their maximum usable temperatures, mineral oils and similar flammable oils reach their flash points at which, in particular apparatus, the evaporation is sufficient to reach the lower explosive limit with air. High volatility is, however, occasionally desirable. In some metalworking operations, working is followed by an annealing operation and any lubricant remaining must evaporate away cleanly.

At low temperatures paraffinic mineral oils reach a lower limit of usage at the pour point. At about $-7\,°C$ a separate wax phase comes out of solution from the rest of the oil and at about $-10\,°C$ sufficient needle-like crystals form to block the flow.

24.4 Mineral oils

The most important type of oil, the mineral oils, are made from petroleum. They are abundant, are comparatively low in cost and are available in a wide range of viscosities. The fatty oils are inferior in all respects except boundary friction properties which, where required, can easily be provided by the incorporation of a low concentration of fatty material. The various synthetic oils are of growing importance and find effective use in extreme applications where some particular property or properties justifies their high price but, in general, their scale of use is very limited.

There are, broadly speaking, two types of mineral oil: paraffinic, having comparatively long alkyl side chains in the molecule and consequently high KVI, together with a 'wax' pour point; and naphthenic, having comparatively short side chains, low to medium VI and a 'viscosity' pour point. With both types a wide range of viscosity grades can be made. Low viscosity mineral oils are frequently known as 'spindle oils' from their early use in textile machinery while the more viscous oils are known as 'cylinder oils' from their use in steam engines. Grades between these two extremes are called 'light machine' and 'heavy machine' oils. These basic grades are produced by refining and intermediate grades are produced by blending.

The wide range of viscosities available is indicated in Figure 24.1 for paraffinic oils of 95 KVI to BS 4231, in which each grade is designated by its mid-point viscosity at 37.8 °C (100 °F) expressed in centistokes ($mm^2 s^{-1}$). Figure 24.1 also indicates in its margins the important classification system of the Society of Automotive Engineers (SAE), the 'W' or winter grades of which are classified in dynamic units, the remainder in Saybolt seconds.

Oxidation stability may be significantly increased by the use of antioxidants as shown in

Figure 24.2, which indicates the life obtainable for a moderate degree of deterioration of a well refined paraffinic oil.

Oxidized oils tend to be corrosive to active metals such as cadmium, zinc and, especially, lead but there is no difficulty in selecting suitable materials of construction since resistant paints and elastomers have been developed over many years.

Typical physical properties for mineral oils are given in Table 24.1.

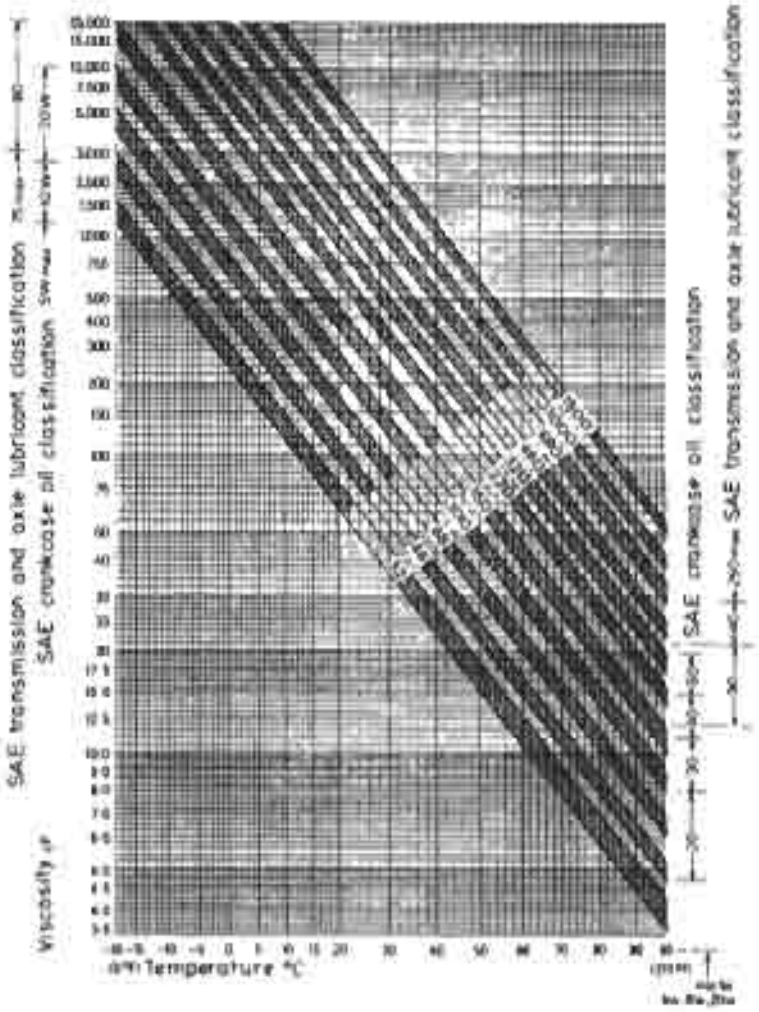


Figure 24.1 BS 4231 ranges for 95 K VI oils with SAE lines.
NB Such oils normally have a pour point of approximately −10 °F, but the lines have been extrapolated to permit comparison with the SAE grades

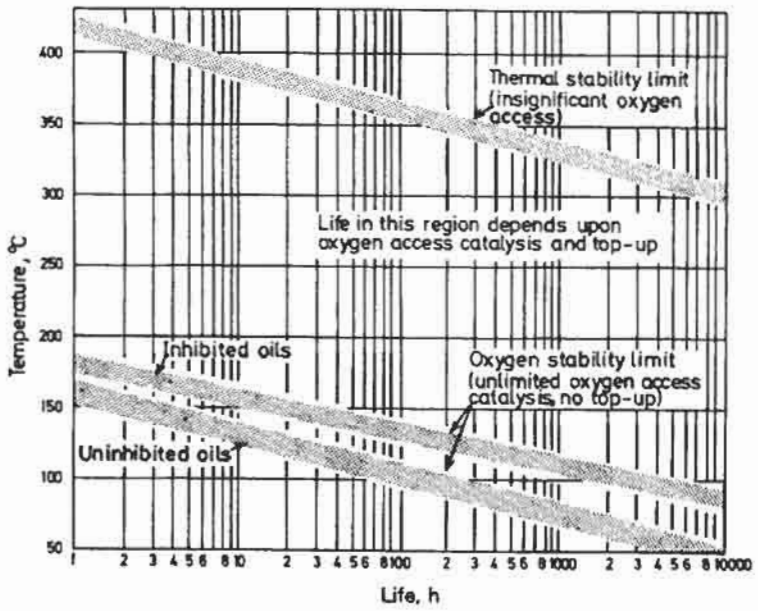


Figure 24.2 *Approximate life of well-refined mineral oils*

Table 24.1 TYPICAL PHYSICAL PROPERTIES OF HIGHLY REFINED MINERAL OILS

	Naphthenic oils			*Paraffinic oils*		
	Spindle	*Light machine*	*Heavy machine*	*Light machine*	*Heavy machine*	*Bright stock*
Density at 25 °C	0.862	0.880	0.897	0.862	0.875	0.891
Viscosity (mN s m^{-2}) at 30 °C	18.6	45.0	171	42.0	153	810
60 °C	6.3	12.0	31	13.5	34	135
100 °C	2.4	3.9	7.5	4.3	9.1	27
Dynamic viscosity index	92	68	38	109	96	96
Pour point, °C	−43	−40	−29	−9	−9	−9
Pressure–viscosity coefficient (m^2 N^{-1} × 10^8) at						
30 °C	2.0	2.8	2.8	2.2	2.4	3.4
60 °C	1.6	2.0	2.3	1.9	2.1	2.8
100 °C	1.3	1.6	1.8	1.4	1.6	2.2
Isentropic secant bulk modulus at 35 MN m^{-2} at						
30 °C	—	—	—	198	206	—
60 °C	—	—	—	172	177	—
100 °C	—	—	—	141	149	—
Thermal capacity (J kg^{-1} °C) at						
30 °C	1880	1860	1850	1960	1910	1880
60 °C	1990	1960	1910	2020	2010	1990
100 °C	2120	2100	2080	2170	2150	2120
Thermal conductivity W m m^{-2} at						
30 °C	0.132	0.130	0.128	0.133	0.131	0.128
60 °C	0.131	0.128	0.126	0.131	0.129	0.126
100 °C	0.127	0.125	0.123	0.127	0.126	0.123
Temperature (°C) for vapour pressure of 0.001 mmHg	35	60	95	95	110	125
Flash point, open, °C	163	175	210	227	257	300

24.5 Emulsions

For many applications, particularly in metalworking and for the provision of fire-resistant lubricants, emulsions of water and lubricating oils are used. Because their thermal capacities are close to that of water, emulsions of 1–10% oil in water are used where heat dissipation is more important than lubrication, as for instance in high speed metal cutting, in grinding and in rolling. Emulsions are also used for fire-resistant hydraulic fluids where a low cost fluid is required. The water should be clean and free from acids with hardness preferably between 15 and 50 p.p.m. $CaCO_3$ equivalent. Very soft water may cause foaming while very hard water may reduce stability and corrosion protection. Oil/water emulsions, however, cannot be used as a direct replacement for oil in conventional hydraulic systems.

Water in oil emulsions with about 40% deionized water are used as cylinder lubricants for reciprocating compressors handling oil-soluble gases and as fire-resistant lubricants to replace oil, however, the presence of water accelerates the fatigue failure of heavily loaded rolling bearings.

Emulsions are non-Newtonian. At high rates of shear their viscosities are close to that of the base oil, which is usually a spindle oil. They are not broken down by shear. Their useful life is largely limited by emulsion stability. To limit loss of water and loss of emulsion stability the maximum continuous operating temperature is about 65 °C.

24.6 Water-based lubricants

Aqueous solutions, either true or colloidal, of various substances are widely used as coolants and lubricants. The water-glycol type of fire-resistant lubricants are solutions of 50–65% polyglycols, sometimes including ethylene glycol. Two or three grades between 0.03 and 0.07 N s m^{-2} at 38 °C (100 °F) are usually available. Their VIs are very high and pour points very low, e.g. −40 °C. They are completely shear stable but operating temperatures are usually limited to 65 °C in order to avoid excessive loss of water.

Solutions of corrosion inhibitors and load carrying additives are used for high speed cutting and grinding operations.

24.7 Synthetic oils

A large number of synthetic lubricants have been described but only a few are of commercial importance.

24.7.1 Diesters

These were developed principally for aviation gas turbines because of their very high VI, and low pour point gives them a wide range of usage while the susceptibility to antioxidants allows them to work continuously at 120–150 °C with bearing temperatures up to 250 °C.

The load carrying capacity of the diesters in spur gear rigs is about twice as high as that of equiviscous mineral oil; under boundary conditions they appear to be equal to mineral oil while in heavily loaded ball and roller bearings the diesters appear to provide somewhat superior protection against surface fatigue.

24.7.2 Neopentyl polyol esters

This group, based on neopentyl alcohols and mixed aliphatic acids, has significantly better thermal stability and the possibility of rather higher viscosity (0.002–0.008 N s m^{-2}) than the diesters. These esters are suitable for continuous operation at 200 °C with hot spots of 275 °C but at these high operating temperatures it is necessary to avoid the use of cadmium, magnesium and silver because of corrosion and to use silicone and fluorinated types of elastomers.

The load-carrying properties of the neopentyl esters are better than those of the diesters, because of their higher viscosity. They apparently do not promote surface fatigue pitting in heavily loaded ball and roller bearings.

Table 24.2 TYPICAL DATA ON FINISHED SYNTHETIC BASED OILS

	Organic acid esters							*Silicones*		
Base oil	*di-(2-ethyl-hexyl) sebacate*	*di(iso-octyl) azelate*	*Mixed C_3–C_6 penta-erythritol ester*	*Mixed C_4–C_{10} dipenta-erythritol ester*	*Triaryl phosphate ester*	*Fluorocarbon*	*Polyglycol*	*Poly-dimethyl (1 000cS at 25 °C)*	*Medium phenyl*	*Chloro-phenyl*
Density at 25 °C	0.911	0.911	1.00	1.02	1.13	1.95	1.02	0.97	1.07	1.01
Viscosity, N s m^{-2}, at 30 °C	0.016	0.016 5	0.032	0.087	0.087	0.280	0.220	0.140	0.170	0.046
60 °C	0.006 5	0.006 77	0.012	0.025	0.019 5	0.038 5	0.070	0.083	0.060	0.027
100 °C	0.002 87	0.003 01	0.005	0.083	0.005 3	0.010 3	0.022 5	0.045	0.022 5	0.015 6
DVI	145	141	144	132	0	−27	164	200	175	197
Pour point, °C	−60	< −65	−60	−50	−18	−15	−25	−55	−50	< −73
Pressure-viscosity coefficient* ($\times 10^{-8}$), $m^2 N^{-1}$, at										
30 °C	1.40	—	—	—	3.3	4.4	1.76	1.81	2.0	—
60 °C	1.28	1.38	1.8†	2.4†	2.0	3.7	1.43	1.81	1.9	2.0
100 °C	1.05	1.18	1.2†	1.6†	1.2	2.83	1.22	1.94	1.9	2.0
Thermal capacity, 1 kg °C, at 30 °C	—	—	—	—	1 510	1 340	1 870	—	—	1 490
60 °C	1 960	1 960	—	—	1 610	—	1 970	1 550	—	1 550
100 °C	2 100	2 100	—	—	1 700	—	2 100	—	—	1 670
Thermal conductivity at 30 °C	0.154	0.151	—	—	0.127	—	0.150	0.162	—	0.150
60 °C	0.149	0.148	—	—	0.127	—	0.148	0.159	0.146	0.145
100 °C	0.142	0.144	—	—	0.126	—	0.146	0.155	—	0.140
Temperature for vapour pressure of 0.001 mmHg, °C	117	93	—	—	125	35	—	177	145	—
Flash point, open, °C	230	243	260	300	—	none	277	316	—	> 273
Approximate cost relative to mineral oil	5	5	10	15	5	300	5	30	60	70

* Average value over pressure range 0–5000 lbf in^{-2} (0–34.5 M Pa). † Estimated

24.7.3 Triaryl phosphate esters

These esters find their greatest use as fire-resistant hydraulic fluids in diecasting machines, and like machines, as well as in the governor systems of large steam turbines. Viscosities range from 0.0036 to 0.008 $N s m^{-2}$ at 100 °C. Their oxidation stability is good, but thermal degradation is catalysed by steel. This limits their maximum operating temperature to about 120 °C. The fire-resistance is on a par with that of the water-in-oil emulsions, and is generally adequate for industrial purposes.

The hydrolytic stability of these esters is rather poor and appears to be catalysed by acid impurities or similar substances developed by initial hydrolysis. If the acidity can be kept low by filtration through fullers earth the degradation can be very greatly retarded. Hydrolysis may result in some corrosion of aluminium and steel but the phosphate esters are not corrosive to cadmium, zinc or other common metals.

Triaryl phosphate esters tend to damage conventional rubber elastomers and therefore butyl, silicone or fluorinated types are preferred. Ordinary paints are also affected and those based on epoxy resins should be used.

These esters are good lubricants under both boundary and hydrodynamic (including elasto-hydrodynamic) conditions but they promote fatigue pitting of rolling element bearings and, for a life equivalent to that when using mineral oils, a 20% reduction in load may be required.

Toxicity is largely related to the amount of ortho-tolyl isomer in the oil which is accordingly kept to a low value. Particular attention should be paid to personal cleanliness and good ventilation wherever people come into contact with these oils.

24.7.4. Fluorocarbons

Usually these are polymers of trifluorovinyl chloride, the terminal groups being fluorine. The range of oils with pour points below 20 °C is only 0.002–0.004 $N s m^{-2}$. Densities and volatilities are unusually high. They are exceptionally stable to strong oxidizing agents such as fuming nitric acid, hydrogen peroxide, etc. Thermally, they are completely stable below 300 °C and the degradation at high temperatures is depolymerization so that carbonaceous deposits are not formed.

Fluorocarbons are non-corrosive to metals. Load carrying capacity under boundary conditions is rather better than that of equiviscous mineral oil, but they may have a lower protection against fatigue failure of heavily loaded rolling bearings.

24.7.5 Polyglycols

These oils are also known as polyalkylene glycols, polyoxyalkylenes, glycols and polyethers. The water soluble types are mainly polyethylene oxides and have high pour points and very high viscosity indices, while the mainly polypropylene oxides are water insoluble with low pour points and somewhat lower viscosity indices. A wide viscosity range is covered: from 0.008 to 19.5 $N s m^{-2}$ at 38 °C.

Polyglycols are very responsive to oxidation inhibitors and when inhibited are much more stable to oxidation than mineral oils. At about 250 °C polyglycols exhibit rapid thermal decomposition, but as the products of decomposition are volatile they do not form deposits. Polyglycols are not corrosive to the usual metals, but since even the water-insoluble grades are slightly hygroscopic rust inhibited grades are preferred wherever moisture may enter the oil.

The water-soluble types have important uses as components of water-glycol type fire-resistant lubricants and automotive brake fluids and are very good lubricants under hydrodynamic and elastohydrodynamic conditions. Under boundary conditions they are not very good but may be provided with suitable properties by the addition of small amounts of long-chain fatty acids.

Typical physical properties of these synthetic lubricating oils are given in Table 24.2.

24.8 Greases

24.8.1 Composition

The standard definition of a lubricating grease is 'A solid to semi-fluid product of dispersion of a thickening agent in a liquid lubricant. Other ingredients imparting special properties may be included.' The most common types of thickener are calcium and lithium metal soaps. Bentonite is

used for high temperatures, above about 140 °C. Esterified silica, vat dyestuffs and urea compounds are used for the most specialised applications.

The fatty acids of the metal soaps also influence the properties of the grease. Mixed acids from tallow, stearic acid and hydroxy stearic acid are probably the most widely used. Complex soaps formed by the co-crystallization of two compounds permit operation at high temperatures.

A grease is usually 80–90% liquid lubricant, commonly low and medium viscosity mineral oil but high viscosity residual oils are used for high temperatures and low speeds. For special purposes, synthetic oils are used.

Additives are commonly used in greases for particular purposes as follows:

Solid lubricants	e.g. graphite, molybdenum disulphide for heavily loaded low speed applications where lubrication will be mainly of the boundary type.
Antioxidants	To prevent rapid oxidation during storage and in use.
Metal passivators	To reduce catalytic oxidation of the grease by cuprous-metals, e.g. in the cages of rolling element bearings. To prevent rusting, particularly of rolling element bearings, during storage and use.
Extreme pressure	To prevent scuffing and wear under boundary lubrication conditions, particularly those arising temporarily from shock loads.

24.8.2 Properties

The essential property of a grease is that it possesses a yield stress up to which it only deforms elastically and above which it flow plastically. When flow commences the ratio shear stress/rate of shear decreases smoothly until at shear rates in the region of $10^6 s^{-1}$ it closely approaches that ratio for the liquid phase of the grease, i.e. its viscosity. Above the yield stress greases are non-Newtonian liquids, and at any point the ratio shear stress/rate of shear is called its 'apparent viscosity', which is, in effect, the viscosity a Newtonian fluid would have if it exhibited the same shear stress at the same shear rate.

The significance of these properties, in relation to plain bearings is that under stationary conditions grease tends to remain in place in clearance spaces and at the ends of bearings. Thus lubricant is available immediately the machine starts up again, and grease clinging to the ends of bearings acts as a seal to exclude dirt.

Semi-fluid greases of negligible yield stress reduce leakage from gearboxes by virtue of their very high apparent viscosity at low rates of shear. They also permit feeding through long narrow bore piping, particularly at sub-zero temperatures.

The yield stress of a grease is not easily measured and for production quality control and other ordinary purposes the worked Penetration (IP 50/69, ASTM D217–C8) i.e. the depth in mm of the penetration in the grease of a special metal cone under its own weight, is used. The National Lubricating Grease Institute has classified greases according to their consistency after a specified amount of mechanical working as follows:

Table 24.3 NLGI GREASE CLASSIFICATION

NLGI grade	*Worked penetration range*
000	445–475
00	400–430
0	355–385
1	310–340
2	265–295
3	220–250
4	175–205
5	130–160
6	85–115

No. 2 grade is popular since it combines satisfactory yield properties with easy pumpability, but where there are extreme vibration and shock loads a No 3 grade is preferred. Grades more fluid than No. 0 or stiffer than No. 3 are not normally used for roller bearings.

Important properties of the thickener structure are temperature stability, resistance to water and mechanical stability. Table 24.4 lists the various types of thickeners and indicates the extent to which they have these properties

Table 24.4 COMPARISON OF GREASE THICKENERS

Thickener type	*Temperature stability*	*Water resistance*	*Mechanical stability*
Calcium soap	Low	Excellent	Excellent
Sodium soap	Good	Poor	Fair
Lithium soap	Very good	Very good	Very good
Modified clay	Excellent	Good	Good

Synthetic oils are used in place of mineral oils for the liquid phase where their special advantages outweigh their greater cost. Diesters are particularly useful where low volatility and good performance at low temperature are needed, e.g. in aircraft bearings. Polyglycols are used where good oxidation stability and good lubrication between steel and bronze are required, also for special cases where the liquid phase is required to evaporate at high temperature without passing through deposit-forming decomposition stages. Silicones are used where good stability is required at high temperatures without the conditions of load and speed being at all severe. Fluorocarbons are, however, preferred in spite of their very high cost where maximum resistance to oxidation is required, e.g. from contact with liquid oxygen or ozone.

24.9 Oil additives

Plain mineral oils are used in many units and systems for the lubrication of bearings, gears and other mechanisms where their oxidation stability, operating temperature range, ability to prevent wear, etc. are adequate. The addition of fatty oils improves boundary lubrication properties at the expense of oxidation stability and demulsibility, but over the last 30 years oil-soluble chemical compounds called 'additives' have been developed which improve or confer a wide range of properties. The functions required of these 'additives' gives them their common names as indicated in Table 24.5.

Table 24.5 TYPES OF ADDITIVE

Main type	*Function and sub-types*
Acid neutralizers	Neutralise contaminating strong acids formed for example by combustion of high sulphur fuels or, less often, by decomposition of active EP additives
Anti-foam	Reduce surface foam
Antioxidants	Reduce oxidation. Various types are: oxidation inhibitors, retarders; anti-catalyst metal deactivators, metal passivators
Anti-rust	Reduces rusting of ferrous surfaces swept by oil
Antiwear agents	Reduce wear and prevent scuffing of rubbing surfaces under steady load operating conditions, nature of film uncertain
Corrosion inhibitors	Type (1) Reduces corrosion of lead. Type (2) Reduces corrosion of cuprous metals
Detergents	Reduce or prevent deposits formed at high temperatures, e.g. in i.c. engines.
Dispersants	Prevent deposition of sludge by dispersing a finely divided suspension of insoluble material formed at low temperature
Emulsifiers	Form emulsions either water in oil or oil in water according to type
Extreme pressure	Prevent scuffing of rubbing surfaces under shock load operating conditions mainly by formation of inorganic surface films
Lubricity	Reduce friction under boundary lubrication condition, increase load carrying capacity especially where limited by frictional temperature rise, by formation of organic surface film. Examples are fatty acids and their esters
Pour point depressant	Reduce pour point of paraffinic oils
Tackiness	Reduces loss of oil by gravity, e.g. from vertical sliding surfaces, or centrifugal forces
Viscosity index improvers	Reduce the decrease in viscosity due to increase of temperature

24.9.1 Machinery lubricants

As shown in Tables 24.6 and 24.7 below, additives and oils are combined in various ways to provide the performance required. It must be emphasized, however, that indiscriminate mixing can produce undesirable interactions. Indeed some additives may be included in a blend simply to overcome problems caused by other additives.

24.9.2 Cutting oils

Factors entering into the selection of cutting oils are: the material of the workpiece; the speed and nature of the operation; whether cooling is more important than lubrication; and the compatibility of the cutting oil with the machine tool.

Table 24.7 gives a very general system of lubricant selection.

Table 24.6 TYPES OF OIL REQUIRED FOR VARIOUS TYPES OF MACHINERY

Type of machinery	*Usual base oil type*	*Usual additives*	*Special requirements*
Food processing	Medicinal white oil	None	Safety in case of ingestion
Plain roll-neck bearings of rolling mills	HVI	None	Best demulsibility
Oil hydraulic	HVI down to −20°C MVIN below	Antioxidant Anti-rust Anti-wear Pour point depressant VI Improver Anti-foam	Minimum viscosity change with temperature Minimum wear of steel/steel
Steam and gas turbines	HVI or MVIN distillates	Antioxidant Anti-rust	Ready separation from water, good oxidation stability
Steam engine cylinders	Unrefined or refined residual or high viscosity distillates	None or fatty oil	Maintenance of oil film on hot surfaces, resistance to washing away by wet steam
Air compressor cylinders	HVI or MVIN distillates	Antioxidant, anti-rust	Low deposit formation tendency
Gears (steel/steel)	HVI or MVIN	Anti-wear EP antioxidant Anti-foam Pour point depressant	Protection against wear and scuffing
Gears (steel/bronze)	HVI	Oiliness, tackiness	Maintains smooth sliding at very low speeds. Keeps film on vertical surfaces
Hermetically sealed refrigerators	MVIN	None	Good thermal stability, miscibility with refrigerant, low floc point
Diesel engines	HVI or MVIN	Detergent Dispersant Antioxidant Acid-neutralizer Anti-foam Anti-wear Corrosion inhibitor	Vary with type of engine thus affecting additive combination

Table 24.7 CHIP-FORMING METALWORKING LUBRICANTS

Type of lubricant	*Base lubricant*	*Additive*	*Remarks*
Soluble oil (oil-in-water emulsion)	LVI oil	Emulsifiers Rust inhibitors	With 20–50 parts water For grinding and light cutting operation where cooling and absence of fuming important

Table 24.7 CHIP-FORMING METAL WORKING LUBRICANTS—*continued*

Type of lubricant	*Base lubricant*	*Additive*	*Remarks*
Aqueous cutting solution	Water	Rust inhibitors	As for soluble oil
Inactive EP cutting oil	HVI	Mild EP but no free sulphur	For cutting yellow metal and other non-ferrous alloys where good lubrication without staining required
Active EP cutting oil	HVI	Mild EP and free sulphur	For heavy cuts on tough steel

24.9.3 Lubricants for chipless-forming

Lubricants for chipless-forming probably present a greater range of diversity than any other branch of lubrication. Table 24.8 gives the types of lubricants used in drawing, stamping and pressing, and Table 24.9 gives lubricants used in rolling.

Table 24.8 TYPES OF LUBRICANTS FOR DRAWING, STAMPING AND PRESSING

Metal	*Lubricant in order of severity of operation*
Steel	Mineral oils of medium to heavy viscosities Fatty oil/mineral oil blends Soap solutions Soap/fat pastes Baked-on-lime coatings Soft metals, e.g. lead
Brass and copper	Dilute soap solutions Light mineral oil Soap/fat pastes with solid lubricants Dried on soap
Magnesium	Colloidal graphite in low volatile mineral oils Graphite in volatile solvents
Aluminium	Oil-in-water emulsions Mineral oils, viscosity increasing with severity Mineral oil with 10–15% fatty oil

24.9.4 Rolling oils

Lubrication is often required in metal rolling but excessive lubricity causes 'lack of bite' or roll slippage. Lubrication affects surface finish, ease of application, removal, and uniformity of adherence to the surface.

Table 24.9 ROLLING OILS

Metal	*Lubricant in order of severity of operation*
Steel	Oil-in-water emulsions Mineral oil/fatty oil blends and with lubricity and EP additives Palm oil
Brass and copper	Oil-in-water emulsion Mineral oil Mineral oil with lubricity additive
Aluminium	Mineral oils of viscosity from 40 mN s m^{-2} at 20 °C to 50 mN s m^{-2} at 40 °C with lubricity additives

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25 Friction and wear

The friction and wear characteristics of materials are not intrinsic properties but, rather, depend on a large number of variables including the physical, chemical and mechanical properties of the material and surfaces and the environment.

25.1 Friction

25.1.1 Friction of unlubricated surfaces

DEFINITION

The friction between two bodies is generally defined as the force which acts between them at their surface of contact so as to resist their sliding on one another. The frictional force F is the force required to initiate or maintain motion. If W is the normal reaction of one body on the other, the coefficient of friction μ is defined as $\mu = F/W$.

STATIC AND KINETIC FRICTION

If the force to initiate motion of one of the bodies is F_s and the force to maintain its motion at a given speed is F_k, there is a corresponding coefficient of static friction $\mu_s = F_s/W$ and a coefficient of kinetic friction $\mu_k = F_k/W$. In some cases these coefficients are approximately equal; in most cases $\mu_s > \mu_k$ and there is a tendency for intermittent or 'stick-slip' motion to occur.

BASIC LAWS OF FRICTION

The two basic laws of friction, which are valid over a wide range of experimental conditions, state that:

1. The frictional force F between solid bodies is proportional to the normal force between the surfaces, i.e. μ is independent of W.
2. The frictional force F is independent of the apparent area of contact.

25.1.2 Friction of unlubricated materials

When clean metal surfaces are placed in contact they do not touch over the whole of their apparent area of contact. The load is supported by surface irregularities (asperities) which deform plastically as the load is applied. The area of real contact is approximately proportional to the load and almost independent of the size and geometry of the surfaces.[1] This is also the case when asperity contact is primarily elastic,[2] which may occur with well run-in surfaces, particularly in the presence of a lubricant or surface oxide films. The limiting values to the true area of contact[3] for a wide range of practical situations are W/p and $10W/p$, where W is normal load and p is plastic flow pressure of the asperities, of the same order as the indentation hardness of the material.

For very clean surfaces strong adhesion occurs at regions of real contact, a part of which may be

due to cold-welding, and these junctions must be sheared if sliding is to take place. Thus, it is almost impossible to slide such surfaces in a vacuum and complete seizure often occurs as shown in Table 25.1. However, if the surfaces are contaminated the adhesion is much weaker because the formation of strong junctions is inhibited. For example, hydrogen or nitrogen atmospheres have little effect on in-vacuo coefficients of friction, but the smallest trace of oxygen or water vapour produces a profound reduction in friction (Table 25.1). A further reduction in the coefficient of friction often occurs at high sliding speeds, particularly at speeds sufficient to produce local hot-spots and surface melting,[4] e.g. ice at 0.1 m s^{-1} or steel at 500 m s^{-1} for which μ may be less than 0.1.

Table 25.1 STATIC FRICTION OF METALS (SPECTROSCOPICALLY PURE) IN VACUUM (OUTGASSED) AND IN AIR (UNLUBRICATED)

	Metals											
Conditions	Ag	Al	Co	Cr	Cu	Fe	In	Mg	Mo	Ni	Pb	Pt
μ_s metal on itself in vacuo	S	S	0.6	1.5	S	1.5	S	0.8	1.1	2.4	S	4
μ_s metal on itself in air	1.4	1.3	0.3	0.4	1.3	1.0	2	0.5	0.9	0.7	1.5	1.3

S signifies gross seizure ($\mu = 10$).

Friction values for metal couples in air depend on a number of factors. Principal ones are the tendency for formation of oxide films, the degree of deformation in sliding, the ability of oxide films to survive sliding contact and the tendency for transfer of material from one surface to the other. Table 25.2 shows the relative hardnesses of some common metals and their oxides and the load (for a spherical slider on polished surfaces) at which appreciable metallic contact occurs. Thus, the oxide on copper is not easily penetrated, whereas the very hard aluminium oxide on the soft aluminium substrate is readily shattered during sliding. Thick oxide films, such as produced by anodizing aluminium, may be more protective because sliding deformation can be restricted entirely to the oxide. Similarly, with very hard metal substrates, such as chromium, the surface deformation may be so small that the oxide is never ruptured.

Table 25.2 BREAKDOWN OF OXIDE FILMS PRODUCED DURING SLIDING

	Vickers hardness (kg mm^{-1})		*Load* (g) *at which appreciable metallic contact occurs*
Metal	*Metal*	*Oxide*	
Gold	20	—	0
Silver	26	—	0.003
Tin	5	1650	0.02
Aluminium	15	1800	0.2
Zinc	35	200	0.5
Copper	40	130	1
Iron	120	150	10
Chromium plate	800	—	Never

Reference: 4.

The static coefficients of friction of a number of metals and alloys on steel are shown in Table 25.3. Of particular note are the values for indium and lead, which are the same as those for sliding on themselves (see Table 25.1). Pick-up occurs on the steel surface such that the sliding couple becomes the metal on itself.

Static friction of ferrous materials is shown in Table 25.4. The data illustrate the effect of increasing hardness on reducing friction through greater support of the surface oxide, the effect of second phases such as carbides and graphite in reducing adhesion of junctions, and the effect of the very thin oxide coating on austenitic stainless steel which is easily ruptured in sliding leading to a high coefficient of friction.

Table 25.3 STATIC FRICTION OF UNLUBRICATED METALS AND ALLOYS (PREPARED GREASE FREE) ON STEEL

The results quoted are for sliders of pure metals and alloys sliding over 0.13% C, 3.42% Ni, normalized steel. The results on mild steel are essentially the same.

Metal or alloy	μ_s	*Metal or alloy*	μ_s
Aluminium (pure)	0.6	Molybdenum (pure)	0.5
Aluminium bronze	0.45	Nickel (pure)	0.5
Brass (Cu 70, Zn 30)	0.5	Phosphor-bronze	0.35
Cast iron	0.4	Silver	0.5
Chromium (pure)	0.5	Steel (0.13 C, 3.42 Ni)	0.8
Constantan	0.4	Tin (pure)	0.9
Copper (pure)	0.8	White metal (tin-base):	0.8
Copper–lead (dendritic: Pb 20)	0.2	(Sb 6.4, Cu 4.2, Ni 0.1, Sn 89.2)	
Copper–lead (non-dendritic: Pb 27)	0.28	White metal (lead-base):	0.5
Indium (pure)	2	(Sb 15,.Cu 0.5, Sn 6, Pb 78.5)	
Lead (pure)	1.5	Wood's alloy	0.7

Table 25.4 STATIC FRICTION OF UNLUBRICATED FERROUS MATERIALS ON THEMSELVES

Alloy	*VPN* $kg\,mm^{-1}$	μ_s	*Alloy*	*VPN* $kg\,mm^{-1}$	μ_s
Pure iron (cold-welded)	150	1–1.2	Ball race steel (Hoffman)	900	0.7–0.7
Normalized steel (C 0.13, Ni 3.42)	170	0.7–0.8	Tool steel (C 0.8, containing carbides)	900	0.3–0.4
Austenitic steel (Cr 18, Ni 8)	200	1	Chromium plate (hard bright)	1 000	0.6
Cast iron (pearlitic)	200	0.3–0.4			

Table 25.5 FRICTION OF VERY HARD SOLIDS

(a) Bonded tungsten carbide (cobalt binder) slider.

Material	μ_s
Tungsten carbide	*c.* 0.2
Aluminium oxide	*c.* 0.25
Copper	*c.* 0.4
Cadmium	0.8–1
Iron	0.4–0.8
Cobalt	0.3

(b) Hard solids sliding on themselves.[4,18]

	Coefficient of friction μ_s		
		Outgassed and measured in vacuo	
Material	*In air at* 20 °C	20–1 000 °C	*Comments*
Aluminium oxide	0.2	—	
Boron carbide	0.2	0.9	Rises rapidly above 1 800 °C
Silicon carbide	0.2	0.6	
Silicon nitride	0.2	—	
Titanium carbide	0.15	1.0	Rises rapidly above 1 200 °C
Titanium monoxide	0.2	0.6	
Titanium sesquioxide	0.3	0.7	
Tungsten carbide	0.15	0.6	Rises rapidly above 1 000 °C

Very hard solids often have low coefficients when sliding on themselves or other materials because of the limited surface deformation that occurs during sliding (Table 25.5).

Similarly, very low coefficients of friction may be obtained by plating hard metal substrates with thin soft metal films (Table 25.6). The substrate supports the load while sliding occurs within the soft film. Typical film thicknesses are 1 to 10 μm.

Table 25.6 FRICTION OF THIN METALLIC FILMS[1]
(Sliding on a 6 mm diameter steel sphere)

	Coefficient of static friction μ_s			
Load g	*Indium film on steel*	*Indium film on silver*	*Lead film on copper*	*Copper film on steel*
4000	0.08	0.1	0.18	0.3
8000	0.04	0.07	0.12	0.2

The friction of many materials is little affected by high or low temperatures (see Table 25.7). Exceptions are when the plastic flow pressure changes significantly or when oxide films become very much thicker.

Table 25.7 FRICTION OF MATERIALS SLIDING ON THEMSELVES AT LOW AND HIGH TEMPERATURES[19,20]

	Coefficient of friction μ					
	Low temperatures in gaseous medium			*High temperatures in air*		
Material	4K	77K	295K	315°C	650°C	980°C
Aluminium	1.52	1.45	1.49	—	—	—
Austenitic stainless steel	0.26	0.35	0.99	—	—	—
Carbon–graphite	—	—	—	0.18	—	—
Copper	0.81	0.78	0.70	—	—	—
Iron	0.97	0.84	0.75	—	—	—
Nickel	1.06	1.10	1.12	—	—	—
Silicon nitride	—	—	—	0.60	0.28	0.48
Tool steel (15Mo15Co)	—	—	—	—	0.30	0.26
Zinc	0.43	0.39	0.52	—	—	—

The friction behaviour of polymers differs from that of metals in three respects. First, the coefficient of friction tends to decrease with increasing load; it also tends to decrease if the geometric contact area is decreased. Second, if the surfaces are left in contact under load the area of true contact may increase with time because of creep and the starting friction may be correspondingly larger. Thirdly, the friction may show changes with speed which reflect the viscoelastic properties of the polymer but the most marked changes occur as a result of frictional heating. Even at speeds of only a few m s^{-1} the friction of unlubricated polymers can rise to very high values. On the other hand at extremely high speeds the friction may fall again because of the formation of a molten lubricating film.

The main effect of speed of sliding is the generation of high local temperatures produced by frictional heating at the regions of real contact. Local hot-spots may produce phase changes or alloy formation at or near the sliding interface, they may produce local melting and they may greatly change the rate of surface oxidation. At speeds of a few m s^{-1} these effects are not as marked as at very high speeds (see Table 25.10) but they may still be significant. In general the kinetic friction at moderate speeds is of the same order as the static friction (compare previous tables) but is usually somewhat smaller. Results in Table 25.9 are for stationary sliders rubbing on a mild-steel disc rotating at a few m s^{-1}. The materials are grouped in descending order of friction. At very high sliding speeds the friction generally falls off because of the formation of a very thin molten surface layer which acts as a lubricant film.[4] Although this is, broadly speaking, the main trend other factors may considerably change the behaviour. For example, with steel sliding on diamond the friction first diminishes and then increases, because at higher speeds the steel is

transferred to the diamond so that the sliding resembles that of steel on steel. In some cases the metals may fragment at these very high speeds particularly if they are of limited ductility. Again, if appreciable melting occurs the friction may rise at high speeds because of the viscous resistance of the liquid interface: this occurs with bismuth.

Table 25.8 FRICTION OF STEEL ON POLYMERS: ROOM TEMPERATURE, LOW SLIDING SPEEDS[4,7,8]

Material	*Condition*	μ
Nylon	Dry	0.4
Nylon	Wet	0.15
Perspex (Plexiglass)	Dry	0.5
PVC	Dry	0.5
Polystyrene	Dry	0.5
Low density polythene (no plasticizer)	Dry or wet	0.4
Low density polythene (with plasticizer)	Dry or wet	0.1
High density polythene (no plasticizer)	Dry or wet	0.15
Soft wood	Natural	0.25
Lignum vitae	Natural	0.1
PTFE (low speeds)	Dry or wet	0.06
PTFE (high speeds)	Dry or wet	0.3
Filled PTFE (15% glass fibre)	Dry	0.12
Filled PTFE (15% graphite)	Dry	0.09
Filled PTFE (60% bronze)	Dry	0.09
Rubber (polyurethane)	Dry	1.6
Rubber (isoprene)	Dry	3–10
Rubber (isoprene)	Wet (water–alcohol solution)	2–4

Table 25.9 KINETIC FRICTION OF UNLUBRICATED MATERIALS SLIDING ON MILD STEEL AT SPEEDS OF A FEW m s^{-1}

Slider	μ_k
Nickel, mild-steel	0.55–0.65
Aluminium, brass (70:30), cadmium, magnesium	0.4–0.5
Chromium (hard plate), steel (hard)	0.4
Copper, copper–cadmium alloy	0.3–0.35
Bearing alloys:	
Tin-base	0.46
Lead-base	0.34
Phosphor-bronze	0.34
Copper-lead (Pb 20)	0.18
Non-metals:	
Brake materials	0.4
Garnet	0.4
Carbon	0.2
Bakelite	0.13
Diamond	0.08

Table 25.10 KINETIC FRICTION OF UNLUBRICATED METALS AT VERY HIGH SLIDING SPEEDS (UP TO 600 m s^{-1}) SLIDING ON A SPHERE OF BALL-BEARING STEEL

Surface	*Duration of expt.* s	*Coefficient of friction* μ_k			
		9 m s^{-1}	45 m s^{-1}	225 m s^{-1}	450 m s^{-1}
Bismuth	1–10	0.25	0.1	0.05	—
Lead	1–10	0.8	0.6	0.2	0.12
Cadmium	1–10	0.3	0.25	0.15	0.1
Copper	1–10	>1.5	1.5	0.7	0.25
Molybdenum	1–10	1	0.8	0.3	0.2
Tungsten	1–10	0.5	0.4	0.2	0.2
Diamond	1–10	0.06	0.05	0.1	≈ 0.1

Reference: 4.

25.1.3 Friction of lubricated surfaces

DEFINITIONS

When moving surfaces are separated by a relatively thick film of lubricant the resistance to motion is due entirely to the viscosity of the interposed layer. The friction is extremely low ($\mu = 0.001 \sim .0001$) and there is no wear of the solid surfaces. These are the conditions of hydrodynamic lubrication under which bearings operate in the ideal case. If the pressures are too high or the sliding speeds too low the hydrodynamic film becomes so thin that it may be less than the height of the surface irregularities. The asperities then rub on one another and are separated by films only one or two molecular layers thick. The friction under these conditions ($\mu \approx 0.05$ to 0.15) is much higher than for ideal hydrodynamic lubrication and some wear of the surfaces occurs. This type of lubricated sliding is called 'boundary' lubrication.[10] The friction does not depend on the viscosity of the lubricant, but on a more elusive property sometimes called 'oiliness'. Under boundary conditions as for unlubricated surfaces the frictional resistance is proportional to the load and independent of the size of the surfaces.

In certain circumstances a further type of lubrication, known as elastohydrodynamic lubrication, may obtain. It arises in the following way.[11,12,13,14] Under conditions of severe loading the moving surfaces may undergo appreciable elastic deformation: this not only changes the geometry of the surfaces, it also implies that very high pressures are exerted on the oil film. The main effect of this is to produce a prodigious increase in the viscosity of the oil. For example at contact pressures of 30, 60, 100 kg mm^{-2} (such as may occur between gear teeth of hardened steel) the viscosity of a simple mineral oil is increased by 200, 40 000 and 1 000 000 fold respectively. Thus the harder the surfaces are pressed together the more difficult it is to extrude the lubricant. Consequently effective lubrication may obtain under conditions where it would normally be expected to break down.

In general, elastohydrodynamic lubrication becomes effective when the oil film thickness is of the order of 10^{-1}–1 μm. This is very much thicker than the boundary film (1–10 nm) but it is very small in engineering terms. Consequently for practical exploitation of elastohydrodynamic lubrication the surfaces must be very smooth and carefully aligned.

25.1.4 Boundary lubrication

Boundary lubricants function by interposing between the sliding surfaces a thin film which can reduce metallic interaction and which is, in itself, easily sheared. The latter criterion restricts boundary lubricants almost exclusively to long chain organic compounds, e.g. paraffins, alcohols, esters, fatty acids and waxes. Radioactive tracer experiments show that while a good boundary lubricant may reduce the friction by a factor of about 20 (from $\mu \approx 1$ to $\mu \approx 0.05$) it may reduce the metallic transfer by a factor of 20 000 or more. Under these conditions the metallic junctions contribute very little to the frictional resistance: the friction is due almost entirely to the force required to shear the lubricant film itself. For this reason two good boundary lubricants may give indistinguishable coefficients of friction, but one may easily give 20 times as much metallic transfer (i.e. wear) as the other. Thus with good boundary lubricants the friction may be an inadequate indication of the effectiveness of the lubricant.

Most boundary lubricants are used as additives, dissolved as a few per cent in a mineral oil:

Table 25.11 LUBRICATION OF STEEL* SURFACES BY PARAFFINS, ALCOHOLS AND FATTY ACIDS STATIC FRICTION

Lubricant	*Length of chain*	μ_s	*Lubricant*	*Length of chain*	μ_s
(a) Paraffins			(c) Fatty acids		
Decane	C_{10}	0.23	Valeric	C_5	0.17
Cetane	C_{16}	0.16	Capric	C_{10}	0.11
Triacontane	C_{30}	0.11	Lauric	C_{12}	0.11
(b) Alcohols			Palmitic	C_{16}	0.1
Octyl	C_8	0.23	Stearic	C_{18}	0.1
Decyl	C_{10}	0.16			
Cetyl	C_{16}	0.1			

* C 0.13, Ni 3.42.

they provide lubrication by adsorbing from solution on to the surfaces. As the temperature is raised the film may dissolve into the superincumbent fluid and lubrication may become ineffective at temperatures appreciably below the melting point of the film itself. The breakdown temperature depends on solubility and concentration, as well as on speed, load, and surface roughness.[15]

With more protracted heating, oxidation of the lubricant occurs and the behaviour is now determined by the properties of the oxidation products themselves. In the early stages these may be beneficial but later they lead to polymerization, gumming and the formation of other deleterious products.

Table 25.12 STATIC FRICTION OF VARIOUS METALS (SPECTROSCOPICALLY PURE) LUBRICATED WITH 1% SOLUTION OF LAURIC ACID (M.P. 44°C) IN PARAFFIN OIL AT ROOM TEMPERATURE

	Coefficient of friction μ_s	
Metal	*Unlubricated*	*Lubricated*
Aluminium	1.3	0.3
Cadmium	0.5	0.05
Chromium	0.4	0.34
Copper	1.4	0.10
Iron	1.0	0.15
Magnesium	0.5	0.10
Nickel	0.7	0.3
Platinum	1.3	0.25
Silver	1.4	0.55

Reference: 4.

Table 25.13 LUBRICATION OF STEEL SURFACES BY VARIOUS LUBRICANTS. STATIC FRICTION

	Static friction μ_s			*Static friction* μ_s	
Lubricant	20°C	100°C	*Lubricant*	20°C	100°C
None	0.58	—	*Mineral oils*		
Vegetable oils			Light machine	0.16	0.19
Castor	0.095	0.105	Thick gear	0.125	0.15
Rape	0.105	0.105	Solvent refined	0.15	0.2
Olive	0.105	0.105	Heavy motor	0.195	0.205
Coconut	0.08	0.08	BP paraffin	0.18	0.22
			Extreme pressure	0.09 ~ 0.1	0.09 ~ 0.1
Animal oils			Graphited oil	0.13	0.15
Sperm	0.10	0.10	Oleic acid	0.08	0.08
Pale whale	0.095	0.095	Trichlorethylene	0.33	—
Neatsfoot	0.095	0.095	Alcohol	0.43	—
Lard	0.085	0.085	Benzene	0.48	—
			Glycerine	0.2	0.25

Table 25.14 LUBRICATION OF METALS ON STEEL. STATIC FRICTION

Bearing surface	*Rape oil* μ_s	*Castor oil* μ_s	*Mineral oil* μ_s	*Long chain fatty acids* μ_s
Hard steel (axle steel)	0.14	0.12	0.16	0.09
Cast iron	0.10	0.13	0.21	—
Gun metal	0.15	0.16	0.21	—
Bronze	0.12	0.12	0.16	—
Pure lead	—	—	0.5	0.22
Lead-base white metal (Sb 15, Cu 0.5, Sn 6, Pb 78.5)	—	—	0.1	0.08
Pure tin	—	—	0.6	0.21
Tin-base white metal (Sb 6.5, Cu 4.2, Ni 0.1, Sn 89.2)	—	—	0.11	0.07
Sintered bronze	—	—	0.13	—
Brass (Cu 70, Zn 30)	—	0.11	0.19	0.13

25.1.5 Extreme pressure (EP) lubricants

Even the best boundary lubricants (e.g. long-chain acids or soaps) cease to provide any lubrication above about 200 °C. Since localized hot-spots of very much higher temperature are often reached in running mechanisms it is necessary to use surface films that have a high melting point and which, as far as possible, possess a low shear strength. One obvious method is to coat the metal with a thin film of a softer metal. These films are effective up to their melting point but are gradually worn away with repeated sliding. Other materials which are very effective are listed in Table 25.15.

Table 25.15 FRICTION OF METALS LUBRICATED WITH CERTAIN PROTECTIVE FILMS

Protective film	*Coefficient of friction* μ_s	*Temperature up to which lubrication is effective*
PTFE (Teflon)	0.05	~320 °C
Graphite	0.07–0.13	~600 °C
Molybdenum disulphide	0.07–0.1	~800 °C

Another approach is to form a protective film *in situ* by chemical attack, a small quantity of a suitable reactive compound being added to the lubricating oil. The most common materials are additives containing sulphur or chlorine or both. Phosphates are also used. The additive must not be too reactive, otherwise excessive corrosion will occur. The results in Table 25.16 are based on laboratory experiments in which metal surfaces were exposed to H_2S or HCl vapour and the frictional properties of the surface examined. The results show that the films formed by H_2S give a higher friction than those formed by HCl: however in the latter case the films decompose in the presence of water to liberate HCl and for this reason chlorine additives are less commonly used than sulphur additives.

The detailed behaviour of commercial additives depends not only on the reactivity of the metal and the chemical nature of the additive but also on the type of carrier fluid used (e.g. aromatic, naphthenic, paraffinic). Further the chemical reactions which occur are far more complicated than originally supposed. With sulphurized additives oxide formation appears to be at least as important as sulphide formation. With phosphates the surface reaction is still the subject of dispute.

Table 25.16 EFFECT OF SULPHIDE AND CHLORIDE FILMS ON FRICTION OF METALS

	Coefficient of friction (μ_s)				
		Sulphide films		*Chloride films*	
Metal	*Clean*	*Dry*	*Covered with lubricating oil*	*Dry*	*Covered with lubricating oil*
Cadmium on cadmium	0.5	—	—	0.3	0.15
Copper on copper	1.4	0.3	0.2	0.3	0.25
Silver on silver	1.4	0.4	0.2	—	—
Steel on steel (0.13 C, 3.42 Ni)	0.8	0.2	0.05	0.15	0.05

Reference: 1.

The differences in friction are not very marked showing that the friction is a very poor criterion of the effectiveness of an EP lubricant. Marked differences in seizure-preventing properties are often

Table 25.17 KINETIC FRICTION, INITIAL SEIZURE LOADS AND WELD LOADS OF BALL BEARING STEEL SURFACES LUBRICATED WITH TYPICAL EP ADDITIVES.[19] FOUR BALL MACHINE FRICTION MEASUREMENTS AT 10 kg LOAD

Lubricant		*Coefficient of friction*	*Initial seizure load*	*Weld load*
Base oil	*Additive*	μ_k	kg	kg
Mineral oil	None	0.09	~45	~120
Mineral oil	Zinc di-secbutyl thio-phosphate (10% wt)	0.09	80	230
Mineral oil	Sulphurized sperm oil (5% wt)	0.095	80	250
	Sulphur	—	65	340
	Chlorinated additive (1% wt)	0.085	85	310
Mineral oil	Tributyl phosphate (1% wt)	—	80	150
Paraffin oil	Tributyl phosphate (1% wt)	—	40	125
Mineral oil	Tricresyl phosphate (1% wt)	—	75	140
Paraffin oil	Tricresyl phosphate (1% wt)	—	40	110

accompanied by almost indistinguishable coefficients of friction. The last four lines of the table also show that EP effectiveness depends to some extent on the nature of the base oil.

25.2 Wear

DEFINITIONS

Wear is the progressive loss of substance from the operating surface of a body occurring as a result of relative motion at the surface. Wear is usually detrimental, but in mild form may be beneficial, e.g. during the running-in of engineering surfaces. The major types of wear are abrasive wear, adhesive wear, erosive wear and fretting. Abrasive wear is wear by displacement of material caused by hard protuberances or particles. Adhesive wear is, strictly, wear by transference of material from one surface to another due to the process of solid-phase welding. Adhesive wear is often used, loosely, to describe other metal-to-metal wear mechanisms, including the removal of particles detached by fatigue arising from cyclic contact stresses and in which no adhesion occurs. Erosive wear is loss of material from a solid surface due to relative motion in contact with a fluid which contains solid particles or collapsing vapour bubbles. Fretting is a wear phenomenon occurring between two surfaces having oscillatory motion of small amplitude and is used, frequently, to include fretting corrosion, in which a chemical reaction predominates.

25.2.1 Abrasive wear

Abrasive wear rates and relative wear resistance (defined as wear of a reference material divided by wear of a test material) vary considerably for abrasives of different hardness, size and shape. Wear rates increase approximately linearly with increasing applied load per unit area up to loads at which extensive failure of the abrasive occurs. Figure 25.1 shows the major effect of relative hardness of the worn surface and abrasive on volume wear rate. Thus, relative wear rates in practice may vary over a wide range, as shown in Tables 25.18 to 25.22. Bulk properties of materials are very approximate guides only to abrasive wear resistance, but wear resistance generally increases as the material bulk hardness increases, except when material is hardened by prior plastic deformation.

25.2.2 Adhesive wear

Metal-to-metal wear involves the contact and interaction of asperities on two surfaces. Local stresses at asperities may be high even when applied loads are low. Adhesive wear is promoted by two major factors:

1. The tendency for different materials to form solid solutions or intermetallic compounds with one another. Thus, material combinations of different crystal structure and chemical properties tend to have lower wear rates and friction. Figure 25.2 illustrates the tendency of metal couples to adhere together.
2. The cleanliness of the surface. Cleaner surfaces are more likely to bond together. Surfaces having a thick oxide film have low wear. Stainless steels and nickel alloys, that do not form thick oxides, have poor adhesive wear resistance.

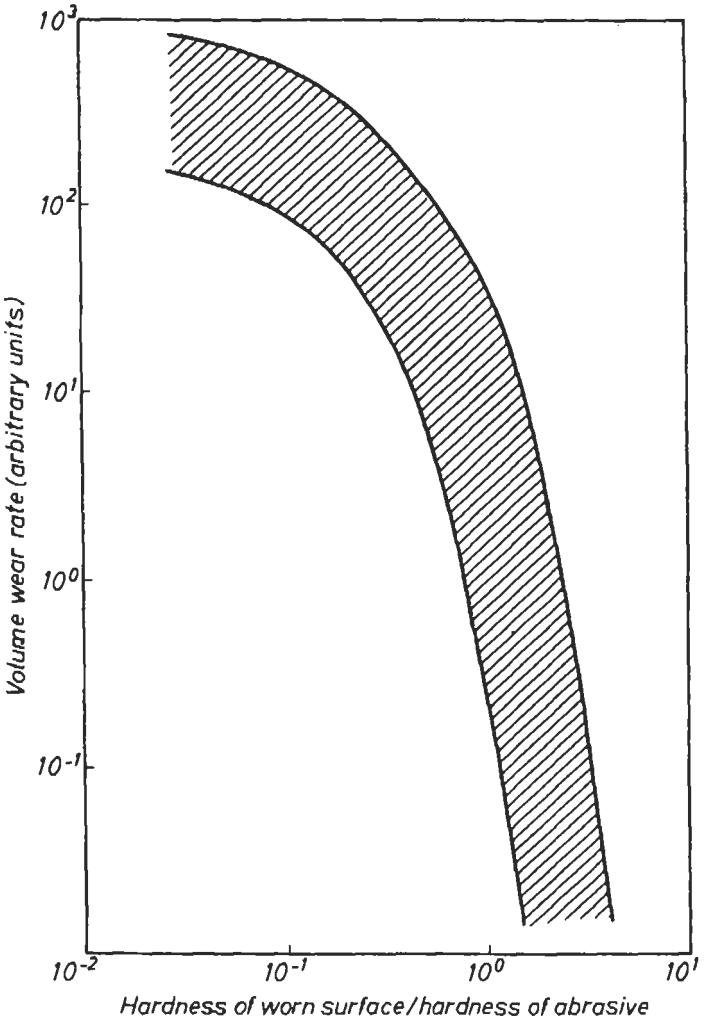


Figure 25.1 *Effect of abrasive hardness on wear rate of metallic materials and ceramics worn on* 80–400 μm *commercial bonded abrasives under an applied stress of* 1 MN m^{-2}.[21,22,23] *(Reproduced from The Fulmer Materials Optimizer by permission of Fulmer Research Institute Ltd.).*

	W	Mo	Cr	Co	Ni	Fe	Nb	Pt	Zr	Ti	Cu	Au	Ag	Al	Zn	Mg	Cd	Sn	Pb
In				2	3				4	3	3	4	4	1	3	4	4	4	4
Pb	2	2	1	1	1	1	1	4	4	4	1	2	3	1	1	3	3	4	
Sn	3		1	3	3	2	3	4	3	4	3	4	4	2	3	2	4		
Cd			3	3	2	2		4	4	3	3	4	4	1	4	4			
Mg		3		3	2	2	2		4	2	4	4	4	4	3				
Zn		3	4	4	4	4	2	4	2	3	4	4	4	4					
Al	4	3	4	3	4	4	4	3	3	4	4	4	4						
Ag	1	2	1	1	1	1	2	4	3	4	3	4							
Au	4	3	4	3	4	4		4	4	3	4								
Cu	2	1	1	4	4	3	2	4	4	3									
Ti	4	4	4	3	4	4	4	4	4										
Zr	3	4	3	4	3	2	4	3											
Pt	4	4	4	4	4	4	4												
Nb	4	4	4	4	4	4													
Fe	4	4	4	4	4														
Ni	4	4	4	4															
Co	4	4	4																
Cr	4	4																	
Mo	4																		

Figure 25.2 *Tendency of metal couples to adhere together. 1 represents the greatest resistance and thus the best combination for wear. 4 represents the least resistance and thus the worst combination for wear. 2 and 3 represent intermediate resistance.*

In metal-to-metal wear, two forms of wear debris are often observed; at very low and very high loads the debris is mainly oxide, but at intermediate loads it is metallic. The transition from oxidative to metallic wear is accompanied by a rapid increase in wear rate. The transition load varies for different materials, microstructures, sliding speed and environment. Thus, wear rates of materials vary by several orders of magnitude (Table 25.23).

Surface treatments are often beneficial in metal-to-metal wear, through a change in surface chemistry, an increase in surface hardness, a change in surface structure or a change in surface topography. Certain coatings are beneficial during running-in, e.g. phosphating and sulphidized coatings, causing metal asperity separation and adherence of lubricant films. Tables 25.24 and 25.25 show the performance of a number of coated and uncoated metal pairs.

25.2.3 Erosive wear

Erosive wear due to the impact of a stream of solid particles is dependent on the size, hardness, velocity and angle of impact of the particles. Wear rate generally increases rapidly with increasing particle size and hardness and impact velocity. For strong and tough materials the maximum wear rate occurs at an impact angle of about 30°, but for hard and brittle materials it occurs at an impact angle of about 90° and for tough and elastic materials at an impact angle close to 0° (Figure 25.3). Thus, material ranking order changes occur for different erosive wear environments.

Table 25.18a COMMONLY USED MATERIAL

Type of material	*Typical commercially available materials*	*Wear rates relative to 0.4% C low alloy steel quenched and tempered to about 500 Vickers hardness*						
		Sliding wear by coke	*Wear by blast furnace sinter**		*Wear of ball mill media/ grinding quartz ores*	*Wear by flint stone sand loam agricultural soil*	*Wear in laboratory jaw crusher, siliceous ores*	*Wear on commercial bonded 384μm flint abrasive*
			sliding	*impact*				
Cast Irons	Low alloy 2.5–2.8% C, ~800 Vickers	1.2	0.8	1.2	~1.0	0.3	—	0.6
	Heat treated nodular graphite, 700 Vickers	1.0	0.15	0.5	—	1.5	—	—
	15/3 Cr/Mo Martensitic	—	—	—	0.8	—	0.04–0.3	0.7–0.8
	High Cr, 25–30%, Martensitic	0.55–0.8	0.15	0.3	0.8	0.3	0.08–0.6	~0.5
	Ni-hard type (3% C, 4% Ni 2% Cr)	0.6	0.07	0.3	~1.0	0.4	0.08	0.6
Steel	0.4% C, low alloy, ~500 Vickers	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Cast And Rolled Steels	0.8% C, ~800 Vickers	—	—	—	~1.0	0.5	—	0.55
	0.3% C, 0.6% Mn, 1.5% Cr, 0.75% Ni, 0.4% Mo, ~450 Vickers	0.3	—	—	—	—	—	—
	0.2% C, 1.2% Mn, 1.3% Cr, 0.25% Mo, 350 Vickers	1.2	0.85	—	—	—	—	—
	2% C, 12% Cr, ~700 Vickers	—	—	—	0.9	0.5	—	0.55
	1% C, 6% Mn, Cr/Mo, austenitic	—	—	—	~1.0	—	0.3–1.3	—
	1% C, 12–14% Mn, austenitic	0.7–1.1	—	1.1	1.2	0.9	0.35–1.4	0.8
Hard Facings (*See also* I.D-MSC) and Table 25.20	3–5% C, 20–30% Cr, Co/Mo/V/W/B Mn/Ni ferrous alloys, manual arc deposited	0.45–0.8	0.09	0.6	—	0.25–0.4	0.7	0.25–0.7
	Tungsten carbide/ferrous matrix, arc or gas tubular rods	—	0.2	—	—	~0.3	—	0.35
	3.5% C, 33% Cr, 13% W, Co alloy	—	—	—	—	0.2–0.5	—	0.45–0.8
	1% C, 1% Fe, 26% Cr, 4% Si, 3.5% B, Ni alloy	—	—	—	—	~0.3	—	0.85

* The Sinter was produced from foreign ore with ASTM ½-strength index of about 47.
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FOR ABRASIVE WEAR RESISTANCE[22–30]

Ease and convenience of replacement	*Typical fields of application*	*Remarks*
Usually convenient with good design to facilitate replacement	Cast irons are very suitable materials to resist medium to high stress abrasive wear due to their good wear resistance and reasonable cost. At very severe levels of impact abrasion, however, inadequate toughness can be a problem and only materials of the work-hardening type should be used. Also cheaper materials may be preferred due to the excessively high wear rates involved	These materials have the merit that a combination of strength i.e. toughness and hardness, may be readily obtained by varying the alloying method of manufacture, and treatment; thus giving suitable combinations of these properties to suit a particular application and wear situation. Various techniques of surface hardening can also be employed to improve resistance to abrasive types of wear. Other products are sintered metals and metal coatings, e.g. Cr plate and sprayed coatings
Usually convenient with good design to facilitate replacement	Due to the very large quantity production involved, steels tend to be comparatively cheap. Thus steels with low wear rates become a competitive materials choice. Their main application lies in hardened steels to resist medium stress abrasion as very low wear rates can be obtained. Austenitic manganese steels can be used in more severe situations due to their work-hardening capability	
Replacement can be difficult if applied *in situ*. These materials are often chosen because hard weld may be built up and worn away several times to its total depth under severe wear situations	For medium and high stress abrasion hard-facings give low wear rates generally, and so are used in many situations to resist abrasive wear, e.g. excavator teeth and other earth moving applications	

Table 25.18b COMMONLY USED MATERIALS FOR ABRASIVE WEAR RESISTANCE

Type of material	*Typical commercially available materials*	*Wear rates relative to 0.4%C low alloy steel quenched and tempered to about 500 vickers hardness*				*Ease and convenience of replacement*	*Typical fields of application*	*Remarks*
		Sliding wear by coke	*Sliding wear by blast furnace sinter*	*Impact wear by blast furnace sinter*	*Wear on commercial bonded 384 μm flint abrasive*			
Ceramics	Fusion cast 50% Al_2O_3, 32% ZrO_2, 16% SiO_2	0.1–0.2	~0.2	0.6	—	Convenient if ceramic is bolted in place. Less convenient if ceramic is fixed by adhesive or cement as long curing times may lead to unacceptably long down-times	Possible to achieve very high hardness but brittleness tends to be a problem	
	Sintered 95–99% Al_2O_3	—	~0.2	~0.7	0.04–0.3		Most suitable to resist low stress abrasion by low density materials and powders	—
	Reaction Bonded SiC	—	6.9	—	~0.02			
	Cast basalt	0.9	0.9	—	~3			
	Tungsten carbide/6% Co	0.07	—	—	0.007			
Glass	Plate glass	4.5	—	—	22	Used in sheet form where transparency is required	Glass is brittle and so it is only used at the lowest levels of abrasive wear	—
Concretes	Aluminous cement-based concrete with proprietary aggregates	3.5	15	—	—	Long curing times can lead to unacceptably long down-times. Can be messy and difficult under dirty conditions	Useful to resist wear of irregularly shaped components and when abrasion is of low to medium stress	Also useful in large flat areas, especially when curing time is no real problem, e.g. aircraft hanger flooring, etc.
	As above with 2% by volume 25 × 0.4 mm diam, wire fibres	—	—	2	—			
	Concrete tile — 6 mm wear resistant surface	—	6.7	—	—			Easily castable
Elastomers	Wear resistant rubbers, 55°–70° shore hardness	7.8	—	—	—	Bonded and bolted. Sticking with adhesive can be difficult under dirty conditions	Very useful to resist impact abrasion – most wear resistant at 90° impact angles. Softer types of rubber are used for low stress impact abrasion. Resilient rubber for more severe impact	Bonding of rubber to component is a very large problem in high stress abrasive wear. Good anti-sticking properties and low density
	65° shore hardness rubber with saw tooth surface profile	15.1	—	—	—			
Plastics	Polyurethane	18.5	2.7	—	—	Usually used in sheet form. Difficult to bond plastic to component. Solid moulded components are superior but are limited to small sizes	Low coefficient of friction, good anti-sticking properties. Best for low stress abrasion by fine particles. Resin bonded aggregates are trowellable and so are useful to resist wear or irregularly shaped components	Composite plastics are only as tough as their bonding matrix and therefore find more applications where low stress abrasion by powders or small particles takes place
	High density polyethylene	15.5–31	—	—	—			
	Epoxy resin based PTFE	40	—	—	—			
	Calcined bauxite filled epoxy resin	11	—	—	—			

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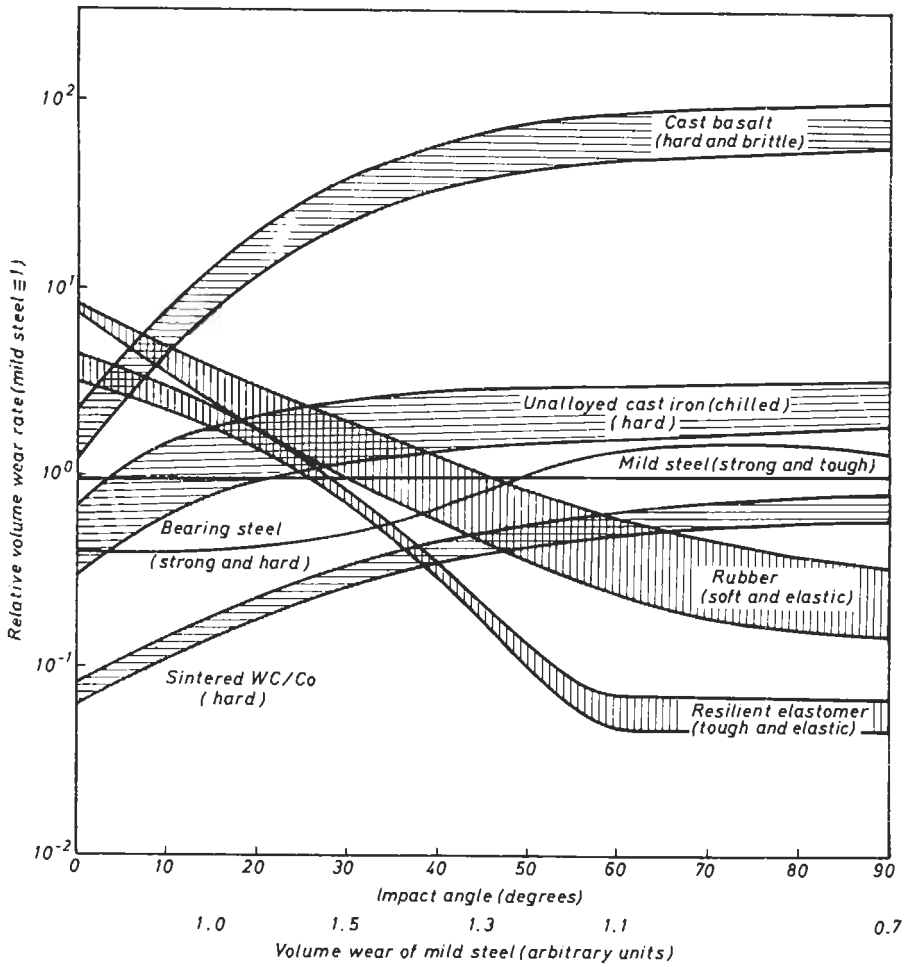


Figure 25.3 *Effect of impact angle on erosion wear of materials impacted with dry 0.2–1.5* mm *quartz.*[36] *(Reproduced from The Fulmer Materials Optimizer by permission of Fulmer Research Institute Ltd.).*

The performance of materials in erosion by sandy water and in pneumatic conveying are given in Table 25.26.

In cavitation, vapour bubbles formed at low pressure collapse in high pressure regions. Cavitation erosion is wear resulting from localized high impact stresses when bubbles collapse at or close to a surface. The cavitation erosion resistance of a range of materials is given in Table 25.27.

25.2.4 Fretting wear

Fretting wear occurs when two contacting surfaces are subject to very small oscillatory slip (of no more than 150 μm). Damage occurs when oxide films are disrupted locally, and may proceed by continuous formation and removal of the oxide, by the abrasive action of the oxide or by localized formation and failure of metal-to-metal adhesive bonds. The rate of fretting wear is normally very low—about 0.1 mg per 10^6 cycles, per MN m^{-2} normal load, per μm amplitude of slip for mild steel. However, localized cyclic stresses may enhance fatigue crack initiation, causing up to 80% reduction in fatigue strength.

Fretting damage is reduced by eliminating slip (by increasing the contact pressure or separating the surfaces) by lubrication (to separate surfaces and wash away debris) and by surface treatments such as electrodeposits of soft metals or chemical conversion coatings of phosphate and sulphidized coatings on steels and anodized coatings on aluminium alloys.

Table 25.19 COMPARISONS OF RELATIVE WEAR RATES OF FERROUS MATERIALS[22,26,31]

		Wear rates relative to 0.4% C, 1½% Ni/Cr/Mo *steel, quenched and tempered to* 500 kg mm^{-2} *(Vickers)*												
		Practical wear environments							*Laboratory wear environments*					
		Agricultural soils			*Quartz/feldspar Mo ores*				*Commercial bonded abrasive discs*				*Rubber wheel*	
Material	*Vickers hardness* kg mm^{-2}	*Pumice*	*Stone free sand*	*Ironstone loam/sand*	*Ball mill*	*Slusher scraper*	*Screen rods*	*Mine car wheels*	84 µm *Corundum* 1 MN m^{-2}	84 µm *Flint* 1 MN m^{-2}	384 µm *Flint* 1 MN m^{-2}	84 µm *Glass* 1 MN m^{-2}	*Dry quartz sand low stress*	*Wet quartz sand high stress*
0.4% C, 1½% Ni/Cr/Mo steel	500	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
0.4% C steel	500	—	—	0.95	—	—	—	—	1.0	0.93	—	0.76	—	—
0.8% C steel	800	0.06	0.43	0.57	—	—	—	—	0.65	0.49	0.56	<0.01	—	—
0.95% C steel	550	—	—	—	—	—	0.77	—	—	0.85	—	0.34	0.81	0.95
2% C, 12% Cr steel	700	—	—	0.52	0.91	—	—	—	0.57	0.09	0.56	—	—	—
1% C, 12% Mn steel	210	0.40	0.83	0.92	1.2	0.83	—	0.59–0.83	0.72	0.63	0.79	0.07	—	—
18/8 Cr/Ni stainless	150	—	—	1.9	—	—	—	—	0.92	0.91	—	1.7	—	—
3% C chilled iron	600	—	—	0.43	1.7	—	—	2.0	0.65	0.23	0.63	<0.01	0.29	1.1
3% C, 30% Cr white iron	700	0.06	0.10	0.44	0.83	—	—	—	0.47	<0.01	0.44	—	0.07	0.51
15% Cr, 3% Mo white iron	900	—	—	—	0.77	—	—	—	—	0.26	0.67	—	—	—
Ni-hard type iron	700	—	—	0.58	1.0	—	—	—	0.66	0.17	0.67	—	0.17	0.47

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Table 25.20 RELATIVE WEAR RATES OF HARDFACINGS[29,31]

Material	*Wear rates relative to 0.4% C, 1½% Ni/Cr/Mo steel at 500 kg mm² Vickers hardness*				
		Commercial bonded abrasives		*Rubber wheel test*	
	Flint clay soil	*34 μm flint* 1 MN m⁻²	*384 μm flint* 1 MN m⁻²	*Dry and low stress*	*Wet sand high stress*
Tubular Fe/70% tungsten carbide, arc weld	0.29	0.04	0.35	—	—
Ni alloy/40% tungsten carbide, fusion spray	0.18	0.04	0.26	—	—
3.5% C, 33% Cr austenitic iron, arc weld	0.24	0.08	0.59	~0.05	~0.95
High C/Cr martensitic iron arc weld	0.44	0.10	0.42	~0.05	~0.87
0.8% C, 3% Ni, 5% Cr, 12% Mn austenitic steel, arc weld	1.01	0.78	0.89	—	—
0.9% C, 4.5% Cr, 7.5% Mo, 1.6% V, 2% W, 1.5% Si, 1.3% Mn martensitic steel, arc weld	0.59	0.79	0.74	~0.29	~0.70
0.95% C, 26% Cr, 4% Si, 3.5% B Ni alloy, fusion spray	0.32	0.12	0.85	—	—
3.5% C, 33% Cr, 13% W Co alloy, gas weld	0.48	0.07	0.78	~0.08	~0.63
97.6% Al_2O_3, 2.5% TiO_2 plasma spray	—	1.64	4.33	—	—
82% Cr, 18% B paste, fused to substrate by gas weld	—	<0.01	0.03	—	—

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Table 25.21 RELATIVE WEAR RATES OF CERAMICS[23,32]

Material	*Vickers hardness* GN m⁻²	*Fracture toughness* K_c MN m$^{-3/2}$	*Wear rates relative to a sintered 95% alumina (bracketed figures relative to 0.4% C, 1½% Ni/Co/Mo steel at 500 kg mm⁻² Vickers hardness)*				
			Commercial bonded flint abrasives				
			84 μm flint 1 MN m⁻²	*384 μm flint* 1 MN m⁻²	*84 μm corundum* 1 MN m⁻²	*84 μm SiC* 1 MN m⁻²	*Diamond sawing*
95% sintered Al_2O_3	12–13	4–6	1.0 (0.024)	1.0 (0.099)	1.0 (0.39)	1.0 (0.81)	1.0
Hot pressed Si_3N_4	~16	5–9	0.32	0.11	—	0.56	1.1
Reaction bonded Si_3N_4	~7	4–5	3.8	8.8	—	2.3	—
Reaction bonded SiC	16–20	7–9	0.15	0.11	—	0.41	—
Hot pressed B_4C	~30	6–9.5	0.21	0.06	—	0.04	0.65
Hot pressed Al_2O_3	14–20	5–7.5	0.3	0.15	—	0.27	—
97.5% sintered Al_2O_3	~15	~8	1.0	0.3	—	0.58	—
99.7% sintered Al_2O_3	~12	~4	1.8	1.4	—	1.2	—
Cast basalt	~5	~2	26	26	—	3	—
Soda-lime glass	4–5	2–4	84	168	100	4.5	—
Sintered TiO_2	~7	~2.5	16	12	—	4.5	—
ZrO_2	15	~2.5	—	—	—	—	1.3
Spinel	16	~1.7	—	—	—	—	2.9
MgO	7	~2.2	—	—	—	—	5.6

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ıble 25.22 RELATIVE WEAR RATES OF CARBIDE COMPOSITES[23,33–35]

mposition TiC + C%	TaC%	*Binder%*	*Carbide grain size* µm	*Vickers hardness* GN m^{-2}	*Fracture toughness* K_c MN m$^{-3/2}$	*Wear rates relative to 4–5% Co composites*						
						Rock drilling		*Laboratory wear tests*				
								Loose abrasive water slurry		*Commercial bonded abrasives*		
						Percussive, granite	*Rotary sandstone*	0.2–0.5 mm Al_2O_3	0.1–0.5 mm SiC/Al_2O_3	84 µm *flint* 1 MN m^{-2}	384 µm *flint* 1 MN m^{-2}	84 µm SiC 1 MN m
		4 Co	1–2	~18	~7	(1.0)	1.0	1.0				
		4 Co	2–3	~16	~10		2.5					
.5	0.5	4 Co		~17					1.0			
	2	5 Co	1–2	~14	~7					1.0	1.0	1.0
		6 Co	1–2	~16	~10	~1.7	1.7	2.0	~1.7			
		6 Co	2–3	~15	~13		5.0	2.5		1.6	1.4	1.6
	1	6 Co	2–3	~13	~7					2.0	1.1	1.5
	2	6 Co		~16.5					1.9			
	22	6 Co		~17					5.3			
		7 Co		~14.5					3.3–4.2			
	3	7 Co		~17					0.5			
.5	12	7.5 Co		~16.5					3.5			
		8 Co	2–3	~15	~12	5.0				2.6	1.9	1.3
		9 Co	1–2	~15	~9	4.0	3.3	5.0				
		9 Co	2–3	~13	~13		6.7	10.0				
.5	6.5	9 Co		~15					6.3			
	20	9 Co		~16					6.3			
	40	10 Co		~17					7.3			
		11 Co		~12		10.0			6.0–7.0			
		13 Co		~11					8.7			
	1	13 Co		~13					7.9			
		15 Co	1–2	~11	18		10.0		~11.0			
		15 Co	2–3	~11	19		25.0	10.0				
	15	16 Co		~13					13.0			
		20 Co		~10.5					18.0			
	80	10 Mo/10Ni		~17					9.0			
		25 Co		~9					20.0			
		30 Co		~8.5					25.0			
% C 1½Ni/Cr/Mo steel				5					850–1 500	530	150	6.3
, C, 12–14% Cr tool steel				~7					140	48	84	~4

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Table 25.23 WEAR RATES OF SOME COMMON ENGINEERING MATERIALS IN UNLUBRICATED SLIDING AT 1.8 m s^{-1} AND A LOAD OF 400 g

Material	*Wear rate* mm^3 mm^{-1}
Mild steel on itself	1.57×10^{-11}
60/40 leaded brass on hardened tool steel	2.4×10^{-12}
PTFE on hardened tool steel	2.0×10^{-13}
Stellite on hardened tool steel	3.2×10^{-14}
Ferritic stainless steel on hardened tool steel	2.7×10^{-14}
Polyethylene on hardened tool steel	3.0×10^{-15}
Tungsten carbide composite on itself	2.0×10^{-16}

Table 25.20 WEAR PERFORMANCE OF COATED AND UNCOATED FERROUS MATERIALS

		Rolling slip (Amsler)						*Sliding*											
		without impact				*with impact*		*Lubricated* 0.1 ms^{-1}		*Unlubricated*									
		Lubricated	*Unlubricated*			*Lubricated*				*Low Load*				*High Load*					
		200 N *Load* V. *Hard*	50 N *Load* V. *Hard*	500 N *Load* V. *Hard*	500 N *Load* V. *Normalized steel*	500 N *Load* V. *Hard*	3000 N *Load* V. *Hard*	*Medium Load* V. *Hard*	*High Load* V. *Hard*	0.1 ms^{-1} V. *Hard*	0.1 ms^{-1} V. *Normalized steel*	1.5 ms^{-1} V. *Hard*	1.5 ms^{-1} V. *Normalized steel*	10 ms^{-1} V. *Hard*	10 ms^{-1} V. *Normalized steel*				
Normalized steels	0.15%C	2																	
	0.45%C	4	3	2						4	4	3	1	6	5				
	0.9%C	5																	
Hardened steels	0.45%C		4	2	3			7	5	5				6	5				
	0.9%C	2																	
Pearlitic cast iron		5																	
Low carbon steel	Carbo-nitrided	3																	
	Carburized	2	4			6	5					4	3	4	4	6	4		
	Nitro-Carburized		4	1	3							4	4	4	4	5	5	5	5

Table 25.24 WEAR PERFORMANCE OF COATED AND UNCOATED FERROUS MATERIALS—*continued*

		Rolling slip (Amsler)						*Sliding*									
		without impact				*with impact*		*Lubricated* 0.1 m s^{-1}		*Unlubricated* Low Load							
		Lubricated	*Unlubricated*			*Lubricated*											
		200 N *Load* *V. Itself*	50 N *Load* *V. Itself*	500 N *Load* *V. Itself*	500 N *Load* *V. Normalized steel*	500 N *Load* *V. Itself*	2000 N *Load* *V. Itself*	*Medium Load* *V. Itself*	*High Load* *V. Itself*	0.1 m s^{-1} *V. Itself*	0.1 m s^{-1} *V. Normalized steel*	1.5 m s^{-1} *V. Itself*	1.5 m s^{-1} *V. Normalized steel*	10 m s^{-1} *V. Itself*	10 m s^{-1} *V. Normalized steel*		
Low carbon steel–*cont.*	Nitrided	3								5							
Alloy steels	Nitrided					5	5	7	5								
	Boronized		4	1	3	4	2	8	6	6		5 6	4 4	5 6	6 6		
	Vanadized					5	4		5	6							
Surface treated normalized medium carbon steel	Tufftride		4	1	2						4 4	4 4	4 4	5 5	5 5		
	Sulfinuz	6	2	1	1						4 4	4 4	5 4	5 5	5 5		
	Noskuff	5	4	3	3						4 4	6 4	6 4	6 4	5 4		
	Sulph BT	5	4	1	1						4 4		3 3	5 5	5 4		

Table 25.24 WEAR PERFORMANCE OF COATED AND UNCOATED FERROUS MATERIALS– *continued*

		Rolling slip (Amsler)						*Sliding*							
		without impact				*with impact*		*Lubricated* 0.1 m s^{-1}		*Unlubricated* Low Load					
		Lubricated	*Unlubricated*			*Lubricated*									
		200 N Load V. Itself	50 N Load V. Itself	500 N Load V. Itself	500 N Load V. Normalized steel	500 N Load V. Itself	2000 N Load V. Itself	Medium Load V. Itself	High Load V. Itself	0.1 m s^{-1} V. Itself	0.1 m s^{-1} V. Normalized steel	1.5 m s^{-1} V. Itself	1.5 m s^{-1} V. Normalized steel	10 m s^{-1} V. Itself	10 m s^{-1} V. Normalized steel
Surface treated normalized medium carbon steel–*cont.*	Sursulf		3	1	2						4 / 4	5 / 4	4 / 4	5 / 5	6 / 5
	Stanal		2	1	1						4 / 4	4 / 4	5 / 4	5 / 4	6 / 4
	Forez		3	2	1							4 / 4	5 / 4	6 / 4	6 / 4
	Phosphate	2													

Key Numerals represent orders of magnitude of wear, i.e. $1 = 10^{-1}$ to 9×10^{-1}, $6 = 10^{-6}$ to 9×10^{-6} in units of volume (mm^3) distance travelled (m). For sliding A/B: A = sweeping element, B = swept element.

* Normalized 0·45% C steel sweeping element

Table 25.25 WEAR IN UNLUBRICATED SLIDING (ROTATIONAL) (0.4 ms^{-1}, 300 kNm^{-2} APPLIED LOAD)

Swept element			*Sweeping Element*				
			Steel annealed	*Grey cast iron*	*0.15% C Steel carburized*	*Tin bronze*	*Brass*
0.15% C steel		Normalized	3.4 / 3.4				
		Carburized	2.4 / 2.3	2.3 / 1.5		1.6 / 1.8	>4.0 / 1.0
		Carburized plus sulph BT	2.4 / 1.6		2.2 / 1.9		
		Carburized plus hard chrome		2.0 / 1.0		2.0 / 1.0	
		Nitrided	2.2 / 2	1.0 / 1.9	1.3 / 1.8	0.3 / 1.6	>4.0 / 1.7
		Boronized	2.4 / 1.0	2.0 / 0.7	1.4 / 1.4	2.1 / 0.8	>4.0 / 1.0
Tool steel		Hardened	2.5 / 2		2.2 / 1.3		
		Titanium carbide (CVD)	1.5 / 0.9	1.5 / 1.2	0.9 / 0.9		
Mo flame sprayed					0.7 / 0.7	1.8 / 0.7	1.9 / 1.0
Al_2O_3 plasma sprayed						2.8 / 1.8	2.1 / 1.0
WC/Co plasma sprayed			1.5 / 1.7	1.3 / 1.0	0.7 / 0.7	1.1 / 0	3.5 / 1.5

Key: Numerical values ≡ LOG_{10} relative wear rate.

A ≡ wear of sweeping element.

B ≡ wear of swept element.

Table 25.26 RELATIVE RESISTANCE OF VARIOUS MATERIALS TO EROSIVE WEAR[37,38]

Materials	*Relative erosive wear resistance*	
	In sandy water	*Pneumatic conveying of minerals*
Ceramics	2–150	—
Aluminas	—	6.5–10
Weld overlays (hard facings)	1.1–20	—
Cast irons	0.5–6	1.2–10
Quenched and tempered steels	—	1.9–5
Rolled and forged steels	1–6	—
Mild steel	1	1
Cast steels	1–2.5	—
Titanium	1	—
Wrought copper alloys	0.3–1	—
Cast copper alloys	0.4–0.9	—
Aluminium alloys	0.1–0.5	—
Plastics	0.04–0.3	—
Elastomers	0.04–0.09	0.12–0.45
Hard Concrete	—	0.11–0.16

Table 25.27 RESISTANCE OF VARIOUS MATERIALS TO CAVITATION EROSION

Range of materials	*Typically used materials*		*High intensity relative cavitation erosion resistance (Aluminium bronze = 1)*	*Remarks*
	Material type	*Specification*		
Cast bronzes	Aluminium bronze	BS1400 AB2	1.3	Aluminium bronze also has good corrosion resistance in sea water, but is more difficult to cast than Novoston bronze
	Aluminium bronze	BS1400 AB1	1.0 (standard)	
	Novoston bronze	BS1400 CMA1	0.5	
	Gunmetal	BS1400 G1	0.22	
	High tensile brass	BS1400 HTB1	0.18	
	Phosphor bronze	BS1400 PB3	0.15	
	Nickel gunmetal	—	0.15	
	Leaded gunmetal	BS1400 LG3	0.14	
Wrought bronzes	Manganese bronze	—	0.2	—
	Everdur A	BS2872 CZ101	0.16	
	Aluminium brass	BS2872 CZ110	0.15	
	Free turning brass	BS2872 CZ121	0.14	
	Naval brass	BS2872 CZ112	0.12	
	Hot stamping brass	BS2872 CZ122	0.11	
	Tellurium copper	BS2872 C 109	0.03	
Nickel alloys	Monel K-500 (aged)	BS3076 NA18	0.7	—
	S Monel	BS3071 NA3	0.5	
	Monel K-500 (cold drawn)	BS3076 NA18	0.3	
	Nimonic 75	DTD 703A	0.22	
	Nickel (hard)	BS3076 NA11	0.21	
	Nickel (annealed)	BS3076 NA11	0.2	
Wrought aluminium alloys	Al 4% Cu solution treated and aged	BS1476 HE15	0.08	
	Al 5% Mg As rolled	BS1476 NE6M	0.04	Low density
	Al 3.5% Mg As rolled	BS1476 NE5M	0.03	
Titanium alloys	Ti-2.25 Al-4 Mo-0.255C-1 1Sn	DTD 5213	1.0	Excellent corrosion resistance
	Ti CP with medium interstitial content	DTD 5273	0.7	Low density. High cost
Cast irons and cast steels	Martensitic stainless	Hardened	1.8	Stainless steels are reasonably corrosion resistant. Martensitic stainless steels are less corrosion resistant than austenitic stainless steels
	Austenitic stainless	Annealed	0.8	
	Ferritic stainless	Annealed	0.77	
	SG cast iron	Tempered	0.7	
	Martensitic stainless	Tempered	0.5	
	Alloy cast iron (D2 Ni-resist)		0.2	

Table 25.27 RESISTANCE OF VARIOUS MATERIALS TO CAVITATION EROSION —*continued*

Range of materials	*Typically used materials*		*High intensity relative cavitation erosion resistance (Aluminium bronze = 1)*	*Remarks*
	Material type	*Specification*		
Wrought steels	HT low alloy	Hardened En24	2.5	
	Martensitic stainless	Tempered En57	0.67	
	Martensitic stainless	Tempered En56	0.62	
	Austenitic stainless	Annealed En58J	0.5	
	Mild steel	En1A	0.2	
Stellites (cobalt alloys)	Stellite 12 (cast) – 29% Cr 9%W 1%C		19.3	Most resistant to high cavitation erosion
	Stellite 4 (cast) – 31% Cr 14%W 1%C		15.0	
	Stellite 6 (cast) – 26% Cr 5%W 1%C		5.3	
	Stellite 6 (wrought)		3.4	
	Stellite 7 (cast) – 26% Cr 6%W 0.4%C		2.5	
Plastics	Nylons, acetals, high impact polyethylenes		1.7–3.0	Values of cavitation erosion resistance fall sharply at elevated temperatures. Generally, plastics with high impact strengths have good cavitation erosion resistance. Very suitable for mass manufacture of small components, e.g. boat propellers. Corrosion resistant
	Polyethylenes, Polypropylenes		0.9–1.6	
	PVC, PTFE		0.15–3.5	
	Chlorinated polyether		0.04–0.1	
	Perspex		0.01–0.035	
Rubbers	Bonded rubber coatings		–	Rubber requires careful preparation and application. Rubber gives satisfactory resistance to mild cavitation erosion, and where relative fluid velocities are low. Failure usually occurs at bond to components at higher fluid velocities
	Neoprene			

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26 Casting alloys and foundry data

26.1 Casting techniques*

Table 26.1 TECHNIQUES USING AN EXPENDABLE MOULD AND PATTERN

	Investment casting				*Full mould*
Equivalent terminology	Lost wax casting Precision casting				Cavity-less casting
Pattern material	Metal, Rubber, Plastic } die Wax, thermoplastics, frozen mercury				Foamed polystyrene or polyurethane
Mould material	Silica base ceramic Slurry + stucco				Silica sand
Binder	Ethyl silicate Magnesium or aluminium phosphate				Usually Na_2SiO_3 or resin (Furane) Can be used unbonded
Size range (kg)	Up to 4.5 except frozen Hg for which up to 45				Up to 5 000 in iron
Scope	Complex shapes and fine detail				One-off castings, e.g. jigs and press tools, complex shapes
Alloys cast	High temp alloys	Steel	Cu base	Al base	Mainly grey iron castings
Surface finish (CLA)	25	25–125	50–85	50–125	No better than 300
Minimum section for length					
25 mm	1.5	1.0	1.5	12	
150 mm	1.5	1.5	1.5	12	
Dimensional tolerance† ± mm					
25 mm	0.13	0.13	0.13	0.6	
150 mm	0.38	0.25	0.18	2.5	
Labour cost per kg	High				Low
Equipment cost per kg	High				Low
Mould material cost	High				Polystyrene pattern approximate cost one third that of wood. Low for unbonded. For other *see* Table 26.2.

* Report No. 187 *PERA*, March 1969.
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† The following additional tolerances should be added if dimension chosen crosses parting line:
Sand ±0.38 Permanent ±0.38 Centrifugal ±0.25
Shell ±0.25 Plaster ±0.25 Shaw ±0.10 to 0.15 for a 25 mm casting.

Table 26.2 TECHNIQUES USING AN EXPENDABLE MOULD

	Ceramic mould casting	*Plaster mould casting*	*Shell mould casting*	*Sand casting*
Equivalent terminology	Shaw process Ceramic shell process	'Antioch' process Gypsum moulding	'C' process Cronig process	—
Pattern material	Wood, plastic, metal	Wood, plastic, metal	Metal	Wood, plastic, metal
Mould material	Molochite, sillimanite, mullite	Calcium sulphate	Silica or zircon sand	Silica, zircon, chromite, olivine, sand
Binder	Ethyl silicate plus gelling agent, e.g. 50/50 NH_4OH/H_2O	Water (autoclave in saturated steam atmosphere at 0.1 $N\,mm^{-2}$ (15 psi) for 6–8 h-stand at amb. temp 14 h)	Phenol-formaldehyde resin (Novolac) + hexamethylenetetramine + heat (from pattern at *c.* 260 °C)	Many variants, e.g. clay, CO_2-silicate, cement, resin self set, silicate self set, etc.
Size range (kg)	Usually up to 180	All sizes	Up to 136	Green sand up to 500, dry sand 500 and above, others to 500 and above
Scope	Complex shapes and fine detail	Limited by pattern withdrawal. Intricate shapes, e.g. wave guides	Better surface finish and accuracy than conventional sand castings	Limited only by pattern work
Alloys cast	Most types: Mg base, Al base, Cu base, steels	Mainly aluminium alloys and some Mg and Cu base	Carbon and alloy steels. Manganese steel. Some stainless and HR steels; Grey, SG and malleable irons; Al, Cu and Mg base alloys	All common foundry alloys; Steel Cast-irons Cu base Al base
Surface finish (CLA)	120 to 180, with fine zircon facing 80 or better	30–40	100–300; 100–250; 100	300–1000
Minimum section for length				
25 mm	2.5 2.5 3.0	Al 1.4 Cu 1.1	4.6 3.2 Al 1.6 Cu 2.3	6.3 3.2 2.3 3.2
150 mm	3.2–4.0 3.2 3.2–4.0	1.4 1.4	6.4 3.5 3.1 3.1	6.3 5.1 3.6 3.6
Dimensional tolerance ± mm				
25 mm	0.18 0.18 0.18	0.13 0.13	0.25 0.25 0.13 0.13	1.52 0.76 0.38 0.38
150 mm	0.30 0.25 0.25	0.18 0.25	0.76 0.76 0.33 0.33	2.54 1.27 0.38 0.38
Labour cost per kg	High	Medium	Low	Low
Equipment cost per kg	Moderately high	Moderately high	Medium to high	Low
Mould material cost	Moderately high	Medium	Medium	Low

Table 26.3 TECHNIQUES USING A NON-EXPENDABLE MOULD (DIE)

	Permanent mould casting (Gravity-die casting)	*Low-pressure die casting*	*High-Pressure die casting (including 'Acurad')*	*Centrifugal casting*	*Continuous casting*
Equivalent terminology	Gravity-die casting chill casting	—	Pressure-die casting Cold-chamber (Al-base) Hot-chamber (Zn base)	'Spun-cast'	'Semi'-continuous (in non-ferrous)
Pattern material	—	—	—	Conventional wood	—
Mould material	Heat-resisting cast iron (expendable cores sometimes used)	Heat-resisting cast-iron (expendable cores sometimes used)	Heat-resistant steel die	Metal die Conventional sand mould	Water-cooled metal die
Binder	—	—	—	—	—
Size range (kg)	Usually 0.45–25 in aluminium but can be up to 250	Up to 11.5 in Al-alloy	Up to 2.25 in brass, 20 in Mg. 34 in Zn, 45 in Al	Pipes up to 1.2m dia. × 11m long. Rings up to 15.2m dia.	Casting speeds vary between 0.04 and 0.11 $m\,s^{-1}$
Scope	Casting design must allow for removal from die	Complex shapes and pressure tight castings	Restricted internal shapes. Die withdrawal	Mainly grey iron pipes and cylinder liners and SG iron pipes and other symmetrical annular shapes	Semi-finished simple shapes (strip, rod, bar) in non-ferrous and grey iron and steel
Alloys cast	All common non-ferrous foundry alloys + some grey iron	Almost exclusive to Al-alloys but steel, cast in USA using graphite mould	Mainly Zn and Al base but some brass and Mg base, Sn and Pb	Highly alloyed steels, grey and SG irons. Most Cu base	Alloy and plain carbon steels, Al and Cu base
	Zn base Cu base Mg base Cast-iron Al base	Aluminium	Zn base Al base Mg base Cu base		
Surface finish (CLA)	100–250	40–100	40–100	Varies widely according to die used and metal cast. Typical range 100–500	100–200
Minimum section for length				Varies widely according to die and metal cast. Typical range 1.8–7.6	Down to 7.6
25 mm	2.5 2.5 6.4	1.3–6.4	1.3 0.8		
150 mm	4.1 5.0 10.2		2.0 1.5		
Dimensional tolerance* ± mm				Dependent on type of die. Usually in region of ±0.64	Usually within 0.13–25 mm
25 mm	0.18 0.38 0.76	0.10	0.10 0.10		
150 mm	0.25 0.53 0.76	0.36	2.00 0.51		
Labour cost per kg	Low	Low	Low	Moderately low	Moderate
Equipment cost per kg	High	High	High	High	High

* The following additional tolerances should be added if dimension chosen crosses parting line:
Sand ±0.38 Parmanent ±0.38 Centrifugal ±0.25
Shell ±0.25 Plaster ±0.25 Shaw ±0.10 to 0.15 for a 25 mm casting.

Table 26.4 MOULDING AND CORE-MAKING MATERIALS.† CLASSIFICATION SPECIFICATION AND PROPERTIES

(a) Typical chemical analyses of moulding and coremaking sands

Origin	SiO_2	Al_2O_3	Fe_2O_3	CaO	Na_2O + K_2O	*Loss on ignition*	*AFS GFN**	*AFS clay content*	*Remarks*
Naturally bonded sands									
Dullatur 40	90.20	5.74	0.91	0.07	1.45	1.56	40	16.4	For steel and heavy iron
Levenseat No. 9	82.63	9.28	1.65	0.31	0.22	4.45	55	20.3	For steel
Dursand High Bond	80.98	9.64	2.55	0.22	1.99	3.32	73	15.7	For steel
Weatherill	80.76	8.90	2.06	0.10	3.36	3.18	76	14.0	For steel
Bramcote	87.50	4.41	2.51	1.00	1.49	2.55	75	8.4	For iron and non-ferrous
Pickering	89.70	4.44	1.36	0.08	1.70	2.00	100	21.1	(Yellow) light iron and non-ferrous
Swynnerton	84.10	7.69	1.91	0.11	3.27	1.80	115	11.4	For iron and non-ferrous
Mansfield Red	82.50	4.96	1.27	2.39 [MgO 1.56]	2.30	2.15	137	13.6	Non-ferrous and some iron
Erith loam	83.80	6.92	2.91	0.52 [MgO 0.83]	2.63	1.95	158	13.2	Iron and non-ferrous
Washed Silica Sands									
Biddulph + 36 mesh	97.65	0.38	0.65	0.10	0.03	0.37	24	—	Sub-angular/angular
Arnold No. 19 (dried)	98.76	0.34	trace	0.11	0.30	0.00	29	—	Rounded/sub-angular
Garside dried No. 21	98.01	0.43	0.90	0.17	0.37	0.00	36	—	Sub-angular
	97.91	1.13	0.50	0.11	0.72	0.21	44	—	Sub-angular
Erith silica	98.97	0.03	0.65	0.05	0.04	0.06	56	—	Sub-angular
Kings Lynn 60 (4F)	98.50	0.78	0.19	0.03	0.35	0.30	66	—	Sub-angular
Redhill 65 (F)	99.50	0.14	0.06	0.00	0.08	0.14	66	—	Sub-angular
New Windsor Rose	97.00	1.50	0.54	0.22	0.93	0.45	68	—	Sub-angular
Chelford Fine (95)	94.70	2.73	0.20	0.10	1.76	0.40	98	—	Sub-angular
Kings Lynn SS (100)	98.40	0.82	0.15	0.03	0.37	0.25	107	—	Sub-angular
Redhill H (110)	99.00	0.27	0.12	<0.01	0.04	0.35	105	—	Sub-angular/angular
Ryarsh	97.50	0.87	0.40	0.03	0.31	0.56	129	—	Sub-angular/angular
Non-siliceous sands									
		ZrO_2		TiO_2					
Zircoruf	33.19	64.90	0.14	0.64	—	0.16	70	—	Zirconium silicate
AMA zircon	32.00	63.40	2.40	0.08	—	0.23	110	—	Zirconium silicate
		Al_2O_3		CaO	MgO				
Olivine No. 2	41.35	0.60	6.25	1.51	48.75	0.33	59	—	Forsterite/Fayalite
Olivine No. $3\frac{1}{2}$	41.76	0.80	6.15	0.84	49.40	0.43	96	—	Forsterite/Fayalite
				Cr_2O_3					
FW chromite	3.10	15.60	26.50	42.00	10.40	under nitrogen 0.23		—	Chromite and other spinels
Fine grade chromite	3.01	12.20	21.50	49.50	12.30	under nitrogen 1.35	111	—	Chromite and other spinels

(b) Typical mechanical analyses of moulding and core-making sands

	Wt.% Retained on British Standard Sieve Mesh No. ‡ (typical)									*Specific § surface*
Origin	16	22	30	44	60	100	150	200	*Thro' 200*	$cm^2\ g^{-1}$
Naturally bonded sands										
Dullatur 40	—	31.8	23.2	16.7	10.3	8.4	3.6	2.0	4.0	—
Levenseat No. 9	0.9	5.3	12.0	15.1	13.9	23.4	5.1	1.4	2.4	122
Dursand High Bond	22.9	2.8	5.4	8.8	13.8	25.1	9.8	8.8	6.0	190

*For comparison purposes only.
†'Data Sheets on Moulding Materials', SCRATA, 3rd Ed. 1972.
‡ For aperture sizes *see* BS410, 1969–*see* Introductory Tables, Table 2.9.
§ Included to give some indication of binder requirement, particularly liquid types.

Table 26.4 MOULDING AND CORE-MAKING MATERIALS:† CLASSIFICATION SPECIFICATION AND PROPERTIES—*continued*

(b) Typical mechanical analyses of moulding and core-making sands—*continued*

Origin	*Wt.% Retained on British Standard Sieve Mesh No. ‡ (typical)*									*Specific§ surface* $cm^2 g^{-1}$
	16	22	30	44	60	100	150	200	*Thro'* 200	
Weatherill	12.4	4.8	5.2	8.5	15.1	29.8	12.9	5.3	5.0	173
Bramcote	—	0.0	0.5	3.0	16.0	45.0	22.0	7.5	6.0	—
Pickering	—	1.9	0.8	0.9	1.5	17.5	57.1	14.2	6.1	—
Swynnerton	—	0.5	0.5	2.2	6.7	26.0	25.0	15.3	23.8	—
Mansfield Red	0.4	0.4	0.4	0.8	1.6	4.4	30.4	22.9	25.1	—
Erith loam	1.0	0.6	0.6	0.4	0.4	1.0	15.5	28.8	38.5	—
Washed silica sands										
Biddulph + 36 mesh	6.7	28.4	40.1	17.3	4.5	1.4	0.6	0.3	0.2	63
Arnold No. 19 (dried)	0.0	0.6	38.5	47.5	10.9	1.6	0.2	0.0	0.0	66
Garside dried No. 21	—	0.6	14.4	49.5	27.8	6.7	0.7	0.1	0.1	75
Chelford W.S. (50)	0.1	1.2	6.4	23.6	44.0	23.8	0.7	0.0	0.0	93
Erith silica	0.0	0.0	0.1	3.6	43.2	50.4	2.2	0.3	0.2	128
Kings Lynn 60 (4F)	0.0	0.0	1.0	7.5	24.4	40.6	13.1	2.3	0.6	162
Redhill 65 (F)	0.3	1.4	4.1	8.5	18.7	42.3	20.2	1.7	0.8	160
New Windsor Rose	0.0	0.1	0.5	3.4	20.9	58.8	14.5	1.3	0.4	133
Chelford Fine (95)	0.0	0.0	0.1	0.3	1.7	49.1	33.2	10.4	4.7	206
Kings Lynn SS (100)	0.0	0.0	0.1	0.2	0.6	16.4	63.6	16.6	2.2	220
Redhill H (110)	—	0.0	0.1	0.4	2.2	22.0	41.6	15.3	17.5	260
Ryarsh	0.0	0.0	0.0	0.2	0.2	1.3	59.0	29.1	7.1	320
Non-siliceous sands										
Zircoru?	—	—	—	0.2	16.0	70.7	12.8	0.1	0.2	73
AMA, zircon	—	—	—	—	0.0	6.8	72.6	19.5	1.0	113
Olivine No. 2	5.6	8.8	13.1	18.7	19.9	19.4	6.0	2.4	5.7	161
Olivine No. 3½	0.2	2.1	5.9	15.1	18.7	24.2	12.4	6.1	14.6	274
FW, chromite	0.3	1.0	4.5	13.7	22.8	32.7	15.1	6.4	3.8	106
Fine grade chromite	—	0.1	0.7	6.0	14.0	28.0	23.5	15.5	12.3	187

† Data Sheets on Moulding Materials', SCRATA, 3rd Ed. 1972.
‡ For aperture sizes *see* BS410, 1969–*see* Introductory Tables, Table 2.9.
§ Included to give some indication of binder requirement, particularly liquid types.

Table 26.5 TYPICAL PROPERTIES OF SOME SODIUM SILICATES USED IN THE CARBON-DIOXIDE, SELF-SETTING SILICATE AND FLUID-SAND PROCESSES*

Grade	*Weight ratio* $SiO_2 : Na_2O$	*Molecular ratio* $SiO_2 : Na_2O$	*Typical analyses % by weight*			*Specific gravity at* 20 °C/20			*Approximate viscosity at* 20 °C cP
			Na_2O	SiO_2	H_2O	*SG*	*Degrees Twaddell*	*Degrees Baumé*	
C112	2.0	2.05	15.2	30.4	54.4	1.56	112	51.8	850
C125	2.0	2.05	16.6	33.2	50.2	1.625	125	55.8	4 500
E100	2.21	2.28	13.2	29.2	57.6	1.50	100	48.1	220
H100	2.4	2.50	12.7	30.8	56.5	1.50	100	48.1	310
H112	2.4	2.5	13.7	33.3	53.0	1.56	112	51.8	2 500
M75	2.9	3.0	9.2	26.8	64.0	1.38	75	39.4	100

* K. E. L. Nicholas, 'The CO_2-Silicate Process in Foundries', BCIRA, 1972.

Table 26.6 TYPES OF MATERIAL USED IN GREEN AND DRY SAND MOULDING*

Class	*Material*	*Approximate AFS/GFN*
A	Naturally bonded sands of medium grain size (Dullatur 40 and other 'rotten rocks')	40
B	Naturally bonded sands of fine grain size (Bramcote)	80
C	Naturally bonded sands of very fine grain size (Mansfield Red)	Over 130
D	Silica sand of medium grain size (Arnold No. 19, Garside No. 21)	30–40
E	Silica sand of fine grain size (Redhill 65, Windsor Rose)	60–70
F	Silica sand of very fine grain size (Ryarsh, Redhill H)	> 100
G	Old sand renovated for further use. Grain fineness depends on original sand	
H	Added clay bond—bentonite	
I	Fuller's earth or other intermediate bonds with proprietory trade names	
J	Fire clay	
K	Organic binders—molasses, sulphite lye solution	
L	Dextrine and other cereal binders	
M	Special additions—coal dust (increasing fines and decreasing quantities for thinner castings), blacklead (graphite), blacking	
N	Sulphur	
P	Boric acid	
Q	Fluoride salts, e.g. ammonium bifluoride NH_4HF_2, ammonium silicofluoride $(NH_4)_2SiF_6$, ammonium borofluoride NH_4BF_4, ammonium fluoride NH_4F	
R	Crushed materials such as 'grog' firebrick or ganister	

* W. H. Salmon and E. N. Simons, 'Foundry Practice', Pitman, London, 1966.

Table 26.7 TYPICAL MIXTURES USED IN GREEN AND DRY SAND MOULDING*

The figures refer to weight percentages and the letters to the materials shown in Table 26.6

Nature of material	*Sand*	*Clay*	*Additions*	*Added moisture %*	*Remarks*
Cast-iron					
Green sand:					
Thin castings	60G 37C		3M	6	
Medium castings	76G 20B		4M	6	
Thick castings	66G 28B		6M	7	NB: Coal dust not used on castings for vitreous enamelling
Synthetic green sand:					
Thin castings	91G	3H	6M	$3\frac{1}{2}$	
Thick castings	54G 36E	4I	6M	$3\frac{1}{2}$	
Non-ferrous					
Copper alloys	70C 30F			7	
Phosphor bronze–dry sand	65G 25C		10M	7	
Aluminium alloys	90G 10C			$6\frac{1}{2}$	+5% P for high Mg alloys
Magnesium alloys	88E	4H	6N, 1P	4	
Steel†					
Synthetic green sand	73E 25D	$1\frac{1}{2}$H	$\frac{1}{2}$L	$3\frac{1}{2}$	
Synthetic dry sand	85G 14D	$\frac{1}{2}$H	$\frac{1}{2}$L	5	
Naturally bonded dry sand	75A 25D			7	NB: For 'Compo' stove to dull red-heat. Highly permeable refractory mixture for very large castings
Compo-dried mould	84R	15J	1M	8	
Loam	40B 40R	10J	10M	15–20	

* W. H. Salmon and E. N. Simons, 'Foundry Practice', Pitman, London, 1966.
† Refractory sand essential for steel casting.

Table 26.8 TYPICAL STANDARD AFS TESTS ON CLAY-BONDED MOULDING SAND MIXTURES*

Casting	*Moisture* %	*AFS green permeability number*	*Compressive strength* 10^4 Pa	
			Green	*Dry*
Cast iron				
Stove plate	9.0	10	4.1	13.8
Radiators	7.0	35	3.4	34.5
Cylinder blocks	6.5	80	4.8	31.0
Average castings	7.0	35	4.1	41.4
Synthetic–thin	3.5	70	5.5	41.4
Non-ferrous copper base				
Small	6.0	25	4.8	28.0
Large	5.5	60	6.9	41.4
Aluminium				
Small castings	7.0	20	3.4	13.8
Large castings	7.0	35	3.4	20.7
Magnesium	4.0	80–150	5.5	69.0
Steel				
Green sand	3.5	180	5.5	48.3
Dry sand	7.5	120	6.2	103
Compo	7.5	40	8.3	172

* W. H. Salmon and E. N. Simons, 'Foundary Practice', Pitman, London, 1960.

Note The tensile strength of sands is less than half the compressive strength.

Table 26.9 TYPICAL MIXTURES FOR THE CO_2-PROCESS AND TYPICAL PROPERTIES OF STANDARD AFS COMPACTS*

Sand	*Silicate*			*Gassing time* s	*Compression strength* (k Pa)	
	Weight ratio $SiO_2 : Na_2O$	°TW	% *Added*		*As gassed*	*After* 24 h *storage*
Chelford 50	2:1	112	4	60	1050	2680
Redhill 65	2:1	112	4	60	860	2140
Erith (56)	2:1	112	4	60	550	2300
King's Lynn (95)	2:1	112	4	60	1700	—

					Gassing time s	*After* 24 h *storage*	
Windsor	2.0:1	112	4	40	1340	30	5600
Rose	2.4:1	112	4	40	2040	24	1790
(68)	2.9:1	100	6	40	1620	18	1035

* K. E. L. Nicholas, 'The CO_2-Silicate Process in Foundries', BCIRA, 1963.

CO_2 flow-rate in all cases 2.5 l min^{-1}.

Table 26.10 SUMMARY OF

Method	*Binder*	*Equipment*
Natural sand	Clay	Wood, metal, or resin core boxes
Synthetic sand core	Clay, usually bentonite	Metal, wood, or resin core boxes
Loam	Clay	Generally strickled on spindle or barrel
Cereals	Starch and corn products Dextrose	Wood, metal, or resin core boxes
Oil	Wide variety including linseed, cotton-seed and fish oils	Wood, metal, or resin core boxes
Cellulose	Water-soluble cellulose ethers and melamine resins	Wood, metal, or resin core boxes
CO_2	Carbon dioxide and sodium silicate plus breakdown agent, e.g. dextrose monohydrate or molasses	Wood, metal, or resin core boxes
Self-setting silicate	Sodium silicate plus one of: (a) Dicalcium silicate (b) Ferro-silicon (c) Organic esters (acetins or glycol diacetates)	Wood, metal, or resin core boxes. Special box paints preferred for (a) and (b)
Air set (no bake)	Oils, usually heat-treated Tung linseed and alkyd resin modified. Catalysts—sodium perborate, 'metal driers', e.g. cobalt naphthenate, and isocyanates	Wood, metal, or resin core boxes
Cold box	Resin (Novolak) isocyanate MDI plus trimethylamine/ air vapour	Gas dispensers Fume extraction Wood, metal, or resin core boxes
Air set (no bake)	(a) Urea-formaldehyde/furfuryl alcohol plus phosphoric acid (b) Phenol–formaldehyde/furfuryl alcohol or (c) Furfuryl alcohol polymer both plus paratoluene sulphonic acid (b) and (c) are nitrogen free	Wood, metal, or resin core boxes
Fascold	Resin (polyurethane) + catalyst (isocyanate) Chemical polymerization at room temperature	Need special core-blowing machine (sand + resin to mix with sand + catalyst) Wood, Metal, Resin } core boxes
Hot box	Phenolic furfuryl or other resin and catalyst (NH_4^+ salts or p.t.s.a.)	Metal core boxes on machine with heating and cooling cycle
Shell	Phenol formaldehyde resin Novalac type plus hexamine catalyst originally. Now usually 'precoated' or 'resin-coated' sands used	Metal core boxes on machine with heating and cooling cycle
Shaw	Ehyl silicate	Accurate and highly finished metal core boxes
Plaster	Gypsum	Accurate and highly finished metal core boxes
SO_2 process	UFFA or Furane polymer resin with peroxide mix	Gas dispensers. Fume extraction. Wood, metal, or resin core boxes

CORE BINDING PROCESSES

Process	*Applications and limitations*
Cores usually baked to develop the clay bond	Suitable for medium and large simple cores for jobbing foundries
Strength developed by baking clay bond	General use for jobbing foundry for all sizes of core. High green strength, good breakdown
Hand-made cores shaped by strickling on straw rope base, clay bond developed by baking	Suitable only for jobbing foundries for simple round and cylindrical cores
Bond developed by baking	Suitable for small and medium cores in jobbing repetition foundries
Oil oxidized by baking to develop bond	For general applications in all foundries but mostly on small and medium work. Poor green strength, and accuracy therefore difficult to maintain
Cores stoved to develop bond	Suitable for jobbing or repetition work. Good breakdown, finish and low gas content
No baking. Core gassed with CO_2 in core box	Suitable for jobbing or repetition work. Fast—accurate—stoving cores, low gas evolution. Main difficulties on breakdown, improved using breakdown agent, but storage life reduced
Silicate cures by either dehydration or for chemical gelling in 0.5–4 h	Suitable for jobbing foundry. Medium to large cores. Good finish. No fume. Breakdown little better than CO_2
Air drying process of 0.5–4 h duration plus 1–2 h baking	Suitable for jobbing foundry and large cores. Good finish, easy breakdown, good green strength, high accuracy
Almost instantaneous hardening in box. Gas passage. e.g. 3s Air purge. e.g. 5s	Sand air must be dry. Good dimensional accuracy. Knockout excellent. Efficient ventilation required. Cores of intermediate size in batches too small to warrant use of shell process
Resin cures after addition of acid in 10–45 min. No baking	Suitable for jobbing foundry and large cores. Good finish, easy breakdown. Good green strength. High accuracy
Both resin and catalyst liquid. Cured in 30–45s Usable 30–60 min after strip	Machine operations are automatic Mass production of small cores—similar sizes to hot-box (Usually for iron-foundry)
Resin cures after addition of catalyst in 10–40s baking at 180–300°C	Suitable only for large quantity repetition work and generally small cores.
Resin cured by heating cycle of 30–120s at 200–400°C	Suitable for large quantity repetition work. Good finish, accuracy and breakdown. High permeability due to shell construction
Conversion of ethyl silicate to silica bond by hydrolysis	For accurate high-temperature metal application where surface finish and accuracy are of prime importance
Hydration of gypsum subsequently dried	For accurate low-temperature applications where surface finish and accuracy are of prime importance
Almost instantaneous hardening by SO_2 gas	Good dimensional accuracy. Knockout excellent. Not sensitive to water

Table 26.10 SUMMARY OF

Method	*Binder*	*Equipment*
FRC (free radical cure)	Acrylic/epoxy resin + organic peroxide/sulphur dioxide gas	Gas dispensers. Fume extraction. Wood, metal, or resin core boxes
Alphaset	Alkalic phenolic resin self setting	Wood, metal, or resin core boxes
Betaset	Alkalie phenolic resin hardened by methyl formate gas	Gas dispenser. Fume extraction (although methyl formate itself is odourless and non-toxic) Wood, metal or resin core boxes

26.2 Patterns—crucibles—fluxing

Table 26.11 CONTRACTION ALLOWANCES OF COMMON ALLOYS (SAND CAST)*

Alloy	*Pattern size* m (in)	*Type of construction*	*Contraction allowance Traditional*	%
Grey cast iron (*see* Note 2)	Up to 0.61 (2.4)	Open	1 in 96	1.04
	0.64–1.22 (25–48)	Open	1 in 120	0.83
	Over 1.22 (Over 48)	Open	1 in 144	0.69
	Up to 0.61 (24)	Cored	1 in 96	1.04
	0.64–1.22 (25–48)	Cored	1 in 120	0.83
	Over 1.22 (Over 48)	Cored	1 in 144	0.69
Cast steel	Up to 0.61 (24)	Open	1 in 48	2.08
	0.64–1.83 (25 -72)	Open	1 in 64	1.56
	Over 1.83 (Over 72)	Open	1 in 77	1.30
	Up to 0.46 (18)	Cored	1 in 48	2.08
	0.48–1.22 (19 -48)	Cored	1 in 64	1.56
	1.24–1.68 (49–66)	Cored	1 in 77	1.30
	Over 1.68 (Over 66)	Cored	1 in 96	1.04
Manganese steel	— —	—	1 in 38 decreasing to 1 in 64 for long castings	2.63 1.56
Mallcable cast iron (*see* Note 3)	—	Section thickness mm (in)		
		1.6($\frac{1}{16}$)	1 in 70	1.43
		3.2 ($\frac{1}{8}$)	1 in 77	1.30
		4.8 ($\frac{3}{16}$)	1 in 80	1.25
		6.4 ($\frac{1}{4}$)	1 in 85	1.18
		9.5 ($\frac{3}{8}$)	1 in 96	1.04
		12.7 ($\frac{1}{2}$)	1 in 110	0.91
		15.9 ($\frac{5}{8}$)	1 in 128	0.78
		19.1 ($\frac{3}{4}$)	1 in 152	0.66
		22.2 ($\frac{7}{8}$)	1 in 256	0.39
		25.4 (1)	1 in 384	0.26
Pearlitic nodular iron, as cast	—	—	1 in 120 to 1 in 180	0.83 to 0.56
Pearlitic nodular iron, heat-treated to ferritic	—	—	1 in 120	0.83

CORE BINDING PROCESSES

Process	*Applications and limitations*
Almost instantaneous hardening by SO_2 gas	Good dimensional accuracy. Knockout excellent. Not sensitive to water + long bench life of mixed sand; to resistant to distortion on casting
The resin is cured with a liquid ester	Environmentally pleasant. Resistant to finning and veining defects. Good surface finish for steel castings
The resin is cured with a gascous ester: methyl formate	Environmentally pleasant. Resistant to finning and veining defects. Good surface finish for steel castings

Table 26.11 CONTRACTION ALLOWANCES OF COMMON ALLOYS (SAND CAST)*—*continued*

Alloy	*Pattern size* m (in)	*Type of construction*	*Contraction allowance Traditional*	%
Nodular iron (thin section) containing carbide as cast and annealed	—	—	1 in 120 contraction to 1 in 240 expansion	0.83 0.42
Aluminium alloys	Up to 1.22 (48)	Open	1 in 77	1.30
	1.24–1.83 (49–72)	Open	1 in 85	1.18
	Over 1.83 (Over 72)	Open	1 in 96	1.04
	Up to 0.61 (24)	Cored	1 in 77	1.30
	0.64–1.22 (25–48)	Cored	1 in 85 to 1 in 96	1.20 to 1.04
	Over 1.22 (Over 48)	Cored	1 in 96 to 1 in 192	1.04 to 0.52
Magnesium alloys (*see* Note 4)	Up to 1.22 (48)	Open	1 in 70	1.43
	Over 1.22 (Over 48)	Open	1 in 77	1.30
	Up to 0.61 (24)	Cored	1 in 77	1.30
	Over 0.61 (Over 24)	Cored	1 in 77 to 1 in 96	1.30 to 1.04
Brass	—	—	1 in 64	1.56
Bronze	—	—	1 in 96 to 1 in 48	1.04 to 2.08
Nickel alloys	—	—	1 in 48	2.08
Everdur (silicon bronze)	—	—	1 in 64	1.56
PMG (silicon bronze)	—	—	1 in 96 to 1 in 64	1.04 to 1.56
High tensile brass	—	—	1 in 120 to 1 in 64	0.83 to 1.56
Aluminium bronze	—	—	1 in 43	2.32
Zinc alloys	—	—	1 in 85	1.18

* From 'Cast Metals Handbook', American Foundrymen's Society.

Notes

(1) Contraction varies with the casting design, type of metal, pouring temperature, and mould or core resistance. It may be necessary to use several different contraction allowances for the various dimensions of a single pattern.

(2) Standard pattern maker's allowance for common grey iron is 1 in 96. For higher strength alloys and white cast irons, the contraction allowance averages 1 in 77.

(3) Contractions shown for malleable irons are net values, e.g. white iron castings which shrink 1 in 48 when cast, expand 1 in 96 during the anneal, giving a net contraction of 1 in 96.

(4) Contraction varies with the alloy. Average values are:

A8, AZ91, C	1 in 85.
Z5Z, RZ5, TZ6, MSR–A, MSR–B	1 in 77
ZREI, ZT1	1 in 64.

Table 26.12 WEIGHTS OF CASTINGS FROM PATTERN WEIGHTS
Multiply pattern weight by the factor shown for the type of wood/metal and the alloys. For wooden patterns, allowance must be made for any metal reinforcement in the pattern.

Pattern material \ *Metal cast*	*Cast steel*	*Cast iron*	*Brass*	*Gun metal or bronze*	*Zinc*	*Copper*	*Aluminium*	*Magnesium*
Mahogany	9.5	8.5	9.5	10.0	8.2	10.1	3.1	2.05
White pine	16.3	14.7	16.5	17.3	14.3	17.5	5.3	3.5
Yellow pine	14.4	13.1	14.7	15.4	12.7	15.6	4.7	3.1
Oak	10.4	9.4	10.5	10.8	9.1	11.2	3.4	2.24
Aluminium alloys	2.87	2.56	2.87	2.98	2.45	3.08	0.93	0.61
Brass	0.98	0.84	0.95	0.99	0.81	1.04	0.31	0.21
Iron	1.09	0.97	1.09	1.13	0.93	1.17	0.35	0.23
White metal	1.08	0.96	1.08	1.11	0.92	1.15	0.34	0.23

Note:
Allowance must also be made for cores and coreprints. For round cores and prints multiply the square of the diameter by the length of the core and prints in inches, and the product by 0.014. This will give the weight of the white pine core in pounds to be deducted from the weight of the pattern.

26.2.1 Pattern materials

(1) Wood: Yellow pine (for limited production) and mahogany (for production patterns) represent the most usual practice.
(2) Metal: (a) Cast iron.
(b) Brass.
(c) Aluminium alloy (e.g. LM6, LM4).
(d) White metal (only to a limited extent because of softness and easily worn away by moulding sand. Used, for example, for lining stripping plates).

Notes:
(1) For small patterns, an alloy of 40% Sn, 18% Sb, 40% Pb, 2% Bi, is used. shrinkage being negligible. Similarly, use is made of a modified 'Wood's metal' (50% Bi, 26.7% Pb, 10% Cd, 13.3% Sn) for making master patterns. It is completely molten at about 70°C and can readily be poured at the temperature of boiling water into wood or plaster moulds.
(2) Contraction allowance for 'master' patterns for casting metal patterns is contraction allowance for casting material, plus contraction allowance for metal pattern material.
(3) Plaster of Paris and proprietory cements: mainly for odd-side impressions.
(4) Plastics: epoxy resins, often reinforced with fibreglass.

Table 26.13 RECOMMENDED STANDARD COLOURS FOR PATTERNS

Part of pattern		*Colour*
As-cast surfaces which are to be left unmachined		Red or orange
Surfaces which are to be machined		Yellow
Core prints for unmachined openings and end prints	Periphery	Black
	Ends	Black
Core prints for machined openings	'A' periphery	Yellow stripes on black
	'B' ends	Black
Pattern joint (split patterns)	'A' cored section	Black
	'B' metal section	Clear varnish
Touch core	Cored shape	Black
	Legend	'Touch'
Seats of and for loose pieces and loose core prints		Green
Stop offs		Diagonal black stripes with clear varnish
Chilled surfaces	Outlined in	Black
	Legend	'Chill'

Table 26.14 GUIDE TO MACHINING ALLOWANCE ADDITIONS TO PATTERN CONTRACTION ALLOWANCES*

Casting alloy	*Pattern size* m(in)	*Bore* mm(in)	*Finish* mm(in)
Cast iron	Up to 0.3 (12)	3.12 (0.125)	2.38 (0.09)
	0.3–0.6 (13–24)	4.76 (0.187 5)	3.18 (0.125)
	0.6–1.1 (25–42)	6.35 (0.25)	4.76 (0.187 5)
	1.1–1.5 (43–60)	7.94 (0.312 5)	6.35 (0.25)
	1.5–2.0 (61–80)	9.53 (0.375)	7.94 (0.312 5)
	2.0–3.0 (80–120)	11.1 (0.437 5)	9.53 (0.375)
Cast steel	Up to 0.3 (12)	4.76 (0.187 5)	3.18 (0.125)
	0.3–0.6 (13–24)	6.35 (0.25)	4.76 (0.187 5)
	0.6–1.1 (25–42)	7.94 (0.312 5)	7.94 (0.312 5)
	1.1–1.5 (43–60)	9.53 (0.375)	9.53 (0.375)
	1.5–2.0 (61–80)	12.7 (0.5)	11.1 (0.437 5)
	2.0–3.0 (80–120)	15.9 (0.625)	12.7 (0.5)
Malleable iron	Up to 0.15 (6)	1.58 (0.062 5)	1.58 (0.062 5)
	0.15–0.23 (6–9)	2.38 (0.093 75)	1.58 (0.062 5)
	0.23–0.30 (9.12)	2.38 (0.093 75)	2.38 (0.093 75)
	0.3–0.6 (12–24)	3.97 (0.156 25)	3.18 (0.125)
	0.6–0.9 (24–35)	4.76 (0.187 5)	4.76 (0.187 5)
Brass, bronze and aluminium alloy castings	Up to 0.3 (12)	2.38 (0.093 75)	1 58 (0.062 5)
	0.3–0.6 (13–24)	4.76 (0.187 5)	3.18 (0.125)
	0.6–0.9 (25–36)	4.76 (0.187 5)	3.97 (0.156 25)

* 'Pattern Makers Manual', American Foundrymen's Society. *Note:* Above pattern sizes quoted, need special instructions.

Table 26.15 MATERIALS FOR PARTING POWDERS AND LIQUIDS

Powder	*Moisture proofer*
Pulverized limestone*	
Precipitated calcium carbonate*	Paraffin wax
Fireclay grog	
Sillimanite	Calcium stearate
Phosphate rock	
Bone ash	Aluminium stearate
Walnut shells	
Ptfe (from aerosol spray)	
Lycopodium powder (very expensive, for art casting only)	
Aluminium powder (as in aluminium paint)	
Liquid—paraffin plus small addition Colza oil	

* React unsatisfactory with chemical binders such as acid-catalysed resin binders

MOULD DRESSING, POWDERS, PAINTS

Table 26.16 SURFACE POWDERS FOR GREEN SAND MOULDS

Non-ferrous	Flour, soapstone, talc (french chalk)
Cast iron	Plumbago, black lead, bituminous coal dust

Material dusted on to mould surface, rubbed in by hand or sleeked with a smooth tool.

Table 26.17 MATERIALS FOR MOULD DRESSINGS

Filler material	*Suspending agent*	*Binder*	*Carrier*
Silica flour	(*a*) *For water base*	Core oil	Water
Zircon flour	Western bentonite	Dextrine	Iso-propyl alcohol
Graphite	China clay	Fire clay	($<5\%H_2O$)
Olivine	Carboxy-methyl-cellulose	Linseed oil	Carbon tetrachloride
Mica	Sodium alginates	Phenolic resin	Toluene
Molochite	(*b*) *For spirit base*	Vinsol resin	Petroleum-ether
Magnesite	Sodium bentonite	Polyvinyl acetate	Methylated spirits
Chamotte	Bentone	Molasses	
Tale			
Plumbago			
Carbon black			

Table 26.18 MIXES FOR WATER-BASED MOULD DRESSINGS*

Alloy type	*Mixture components %*				*Added water %*
Copper base	20A	6.6B	6.6C		66.6
High lead or phosphor bronze	11.5D	23B	8.5C		57
Cores for heavy section bronze		34E			66
Aluminium	22A	11F	11C		56
Cast-iron					
Blackwash	22G	4 H or C			74
Blackwash	21G	4L	4H		71
Heavy section	20J	6.6L	6.6B		66.6
Heavy section	25K	6L	3H	3M	63
Steel					
Light section	30K	1.5L	4.5M		64
Facing mix	45J	1.5D	4H		49.5
Manganese steel	42.5N	5L	2.5H		50
Zircon to 1.8Sp.G. (65 °CBé)	60P	4L	1Q		35

* W. H. Salmon and E. N. Simons, 'Foundry Practice', Pitman, London, 1966.

A. Talc.
B. Plumbago.
C. Molasses.
D. China clay.
E. Sodium silicate.
F. Whitening.
G. Blackening.
H. Dextrine.
J. Chamotte (200 mesh).
K. Silica flour.
L. Bentonite.
M. Core oil.
N. Magnesite.
P. Zircon (200 mesh).
Q. Core cream.

Table 26.19 TYPICAL 'SPIRIT BASE' OR 'FLASH-OFF' DRESSINGS

Component	*Polar solvent carrier*		*Non-polar solvent carrier*	
	Description	*p.b.w.**	*Description*	*p.b.w.**
Refractory filler	Zircon flour (200 mesh)	69.0	Zircon flour (300 mesh)	29.0
Suspension agent	Bentone 18C + pure grade toluene	2.8 1.5	Bentone 34 – Ind. meths (64 o.p.)	1.0 0.4
Resin binder	Novolac type	1.3	Cumarone/Indene type	2.0
Carrier	Iso-propyl alcohol	25.0	White spirit (SBP6)	31.6

* p.b.w.—parts by weight.

Table 26.20 MOULD COATINGS FOR SPECIAL APPLICATIONS

Cast metal	*Coating constituent(s)*	*Purpose*	*For further information consult*
Aluminium base alloys	Acetylene soot	Increased fluidity,	—
	Hexachlorethane-containing wash	Increased fluidity + refined grain	—
Copper base alloys	325 mesh molochite Powdered vinsol resin 99% Iso-propyl alcohol	Prevention of 'steam' reaction at metal–mould interface resulting in globular sub-surface porosity	BNFMTC
Phosphor-bronzes and gunmetals	Finely divided Al–Mg alloy suspended in a solvent (e.g. toluene)	Prevention of pinhole porosity	BNFMTC
Grey iron	Finely divided bismuth	Suppresses micro-shrinkage porosity in 'hot spots'	BCIRA
Grey iron	Finely divided tellurium	Local chilling for additional hardness	BCIRA
Malleable irons	Zinc/ground coke or cobalt, cobalt/iron oxide	Prevents hot-checking on white-iron castings and modifies dendrite structure	BCIRA

BNFMTC—British Non-Ferrous Metals Technology Centre. BCIRA—British Cast Iron Research Association.

26.2.2. Crucibles and melting vessels

Refractory crucibles were originally produced from clay alone, but since the beginning of the century most melting crucibles have incorporated up to 30% graphite, bonded with clay, to improve thermal shock resistance, erosion from fluxes and conductivity. Additions of silicon carbide are also made where higher duty is required. The life of crucibles has been improved over recent years by development of glazes which protect the crucible against oxidation or 'perishing'.

Carbon-bonded silicon carbide crucibles made from silicon carbide and graphite bonded with tar, which on firing produces a carbon bond, have superior thermal shock resistance and improved performance against flux attack and oxidation under certain conditions. 80% of crucibles manufactured in recent years are produced from carbon-bonded silicon carbide. They are generally more expensive than clay-graphite crucibles.

TYPES OF CRUCIBLES

Three types of crucibles are in general use for non-ferrous work. These are:

1. *Crucibles used in pit or 'pull-out' furnaces*
 A and C shape which have to be removed from the furnace for metal to be poured.
 These vary in size from a few kilograms to greater than 1000 kg brass capacity, though the latter sizes are not generally used on account of the difficulty of handling them. In oil- and gas-fired furnaces the crucible rests on a small stand or stool—of similar material to the crucible, and a ring or cylinder to accommodate and protect protruding solid metal is sometimes placed on the top of the crucible. The chief value of the pit furnace lies in its flexibility and low capital cost and it is ideal for small or medium-sized foundries where relatively small quantities of a variety of metals or alloys are required.
2. *Crucibles used in tilting furnaces*
 For convenience in pouring or where the size of crucible is such it cannot be readily handled, it is mounted permanently in the furnace, which is tilted to discharge its molten contents.
 Crucibles varying from 70 kg to greater than 760 kg brass capacity are in general use, though larger crucibles and furnaces are now available with capacities of up to 1520 kg brass (590 kg aluminium)
3. *Maintaining crucibles*
 Crucibles or basins for holding molten metal for periodic casting or for process work are extensively used for purposes such as die casting.
 Those used for die casting are usually of basin shape and are wide in proportion to their height. They are made in sizes up to 600 kg aluminium capacity for aluminium die casting, or 135 to 180 kg brass capacity for aluminium bronze or brass die casting.
 Silicon carbide basins are particularly suited to maintaining molten aluminium alloys for die casting, as neither aluminium nor aluminium oxide attack the crucible material.

26.2.3 Iron and steel crucibles—fluxing

Steel crucibles are normally used for the melting of magnesium alloys. Low carbon steels are used and nickel and cobalt should be absent from the steel because of the adverse effect of even small traces of these elements on the corrosion resistance of magnesium alloys.

The crucibles may be of a pressed construction or made up of welded boiler plate.

For very large melts, cast-steel (~0.4% carbon) crucibles are used.

Although cast-iron crucibles were often used in holding furnaces for aluminium alloy die casting, they appear to have fallen out of favour and are now rarely found in use.

Where they are still used a refractory wash of similar nature and composition to the following:

Finely ground whitening	9 wt.%
Water	90 wt.%
Waterglass (hot conc. soln)	1 wt.%

applied daily will minimize iron contamination.

Silicon carbide or plumbago basins are used in preference to cast-iron pots nowadays, for aluminium melting.

Table 26.21 COMMON FLUXING AND INOCULATION

Alloy group	*Cover fluxes*	*Degassing and/or cleansing fluxes and treatments*
Most aluminium alloys (except Al–Mg, *see* below)	(a) $NaCl + NaF$ (or cryolite) $+ KCl$ + small amounts of $SO_4^{2-} + NO_3^-$ (b) $Na_2SiF_6 + NaCl$ ↓ also used for metal recovery from drosses (c) Reverberatory furnaces (typical): $CaCl_2$ 50%, NaCl 30%, KCl 20% (d) Rotary furnaces (typical): NaCl 45%, KCl 45%, Cryolite 10% } m. pt 607°C	(a) Inert gases N_2, He, Ar [Response time slowest] [Use N_2 at < 700°C or – AlN formation Use N_2 at ≤ 670°C with Al-Mg alloys or → Mg_3N_2 formation] (b) Inert active gas mixtures e.g. $90N_2/10Cl_2$ [Response time reasonably fast] (c) Active gases Cl_2, F_2 or compounds containing them, e.g. hexachloroethane C_2Cl_6 and Freon 12 CCl_2F_2 [Response time fast] (d) Metal chlorides $ZnCl_2$, BCl_3, $CuCl_2$, $MnCl_2$, $TiCl_2$ } Careful selection to prevent contamination. All hygroscopic
Aluminium–magnesium alloys (3–10% Mg)	Similar to magnesium alloys. Mixtures of chlorides and fluorides, e.g. $MgCl_2 + KCl + MgF_2$ or CaF_2 *NB*: No sodium compounds of any description if present → embrittlement, hot-shortness	Groups (b) and (c) above (20% Mg loss at 690°C 90% Mg loss at 710°C, 50% Mg loss with C_2Cl_6 regardless of temperature) Also used—K_2ZrF_6, Ti sponge
Magnesium alloys		Degas with (a) C_2Cl_6 (b) Cl_2 (c) N_2 'Flux bubbled' [$MgCl_2$ rich flux on crucible bottom 650–680°C]
(a) Mg, Mg–Al, Mg–Mn	$CaCl_2$ 40%, NaCl 30%, KCl 20%, $MgCl_2$ 10% } 'Melrasal Z'	$MgCl_2$ 35%, $CaCl_2$ 15%, NcCl 10%, KCl 10%, CaF_2 20%, MgO 10% } Inspissating flux 'Melrasal E'
		$CaCl_2$ 19%, NaCl 11%, KCl 7.5%, $BaCl_2$ 37.5%, MgF_2 25% } For holding furnaces. $BaCl_2$ addition to increase density
	'Melrasal UE' all-purpose flux (melting, refining, covering) made up of 1 part 'Z' flux to 6 parts 'E' flux	
(b) Mg–Zr	$BaCl_2$ 39%, $MgCl_2$ 30%, KCl 10%, BaF_2 21% } for alloys containing rare earths: $BaCl_2$ 28%, $CaCl_2$ 26%, KCl 10%, NaCl 16%, MgF_2 20% $BaCl_2$ 40%, $MgCl_2$ 35%, KCl 10%, MgF_2 15% } for alloys containing thorium	Zr acts as its own degasser $Zr + 2[H]Mg \rightarrow ZrH_2 \downarrow$
Copper-base alloys HC Copper	Charcoal	Degas N_2 only if necessary Deoxidation: 15% phosphor-copper (equiv. to 0.005% P) followed by CaB_2, Li (0.003–0.01%) or 10% Be–Cu (0.005–0.02% Be)

PRACTICES FOR VARIOUS ALLOYS

Special purpose fluxes and inoculants

(1) Grain refinement
 (a) Combined additions of K_2TiF_6 + KBF_4 + (sometimes) C_2Cl_6 for better efficiency
 KBF_4 used alone if alloy contains Ti near maximum specified
 (b) Using a 'hardener', e.g.: Al–5% Ti–1%B

(2) 'Modification' of Al–Si alloys

 (a) Eutectic or near-eutectic (11–14% Si)
 Salt mixtures containing NaF,
 e.g. 88% NaCl–KCl (1:1) + 12% NaF (fuses at 607 °C)
 Vacuum-melted sodium sealed in air-tight Al containers
 or Sr { Sr modification lasts for several hours; Sr modified alloys can be remelted without loss of fine structure

 (b) Hypereutectic (17–25% Si)
 Red phosphorus introduced as particles (< 60 μm) in a mixture of KCl and K_2TiF_6. Effect strengthened if subsequent Cl_2 treatment

Grain refinement with salt mixtures as in 1(a) above

Grain refinement:

Alloy type	*Treatment*	*Degree of grain refinement achieved*
Mg–Al(–Zn–Mn)	Carbon inoculation (C_2Cl_6)	Marked
	Superheat to ≥ 850 °C	Marked
Mg–Al–Mn(–Zn)	$FeCl_3$	Marked
Mg–Zn(–RE–Mn)	$FeCl_3$, Zn–T% Fe alloy, or NH_3	Very marked
Mg–Mn	$Ca + N_2$	Mild
	Zr	Increases with falling Mn content
Mg–Zr	Use master alloy (proprietory) 'ZIRMAX'	
	Max gr. ref. at max solubility of Zr (0.6%)	
	Zr will not grain refine in presence of: Al, Si, Sn, Ni, Fe, Co, Mn, Sb	Zr will grain refine in presence of: Zn, Cd, Ce, Ag, Th, Tl, Cu, Bi, Pb, Ca

Protection:
(1) 'Dusting' fluxes S, NH_4BF_4, NH_4HF_2, NH_4F, H_3BO_4 e.g. S + 5 to 30% H_3BO_4
(2) SO_2 atmosphere 'Purge' mould prior to cast

Table 26.21 COMMON FLUXING AND INOCULATION PRACTICES FOR VARIOUS ALLOYS—*continued*

Alloy group	*Cover fluxes*		*Degassing and/or cleansing fluxes and treatments*
Gunmetals	Charcoal	C(≥25 mm thick)	Degas with dry N_2
	Borocalcite	$4CaO{\cdot}5B_2O_3{\cdot}9H_2O$	(e.g. 45 kg melts at 5–10 l min^{-1} for about 5 min)
	Boric oxide	B_2O_3 (crucible attack)	or use 'oxidation-reduction' technique
	Borax	$Na_2B_4O_7{\cdot}10H_2O$	
	Soda ash	Na_2CO_3 (*desulphuriser*)	*Oxidizing agents* / *Deoxidants*
	Common salt	NaCl	Cupric oxide CuO — 15% P–Cu
	Calcium fluoride	CaF_2	Cuprous oxide Cu_2O* — Lithium
	Silica sand	SiO_2	Manganese dioxide, Manganese ore, MnO_2† — 10% Li–Cu, 98% Zn–2% Na
	Glass (green bottle)	—	Barium peroxide BaO_2
	Barium carbonate	$BaCO_3$ (desulphuriser)	
	Calcium oxide (lime)	CaO	[*Reduced by H_2 to Cu, does not evolve oxygen; †Also removes As, Fe, Si and S]
Tin bronzes	Typical: Fused borax 30, dry silica sand 50, cupric oxide 20:2.75 kg charge Electric furnace melting: 3 parts lime + 1 part fluorspar		
Brasses and high tensile brasses	Charcoal, borax, greenbottle glass ↓ Virgin melts; ↳ All scrap melts		None usually practised (Zn, Al, Mn are all deoxidants)
Aluminium bronzes	Manganese chloride ($MnCl_2$), Cryolite (AlF_3–3NaF) } Both reduce crucible life (Do not use compounds containing boron)		Degas with dry N_2 or CO_2
Silicon bronzes	Bottle glass + small % of fluoride salts (Pb free) Can be thickened before skim with silica sand. *NB*: Not charcoal		Degas with dry N_2 or CO_2 Deoxidation not required
Nickel silvers	Broken glass, 80:20 borax–boracic acid, Borocalcite, all Pb free. *NB*: not charcoal. Thicken for removal with powdered CaO		Deoxidation 0.1% Mn + 0.06% max. Mg (Mg also desulphurizes)
Copper-nickels and Monels	As for Ni-Silvers + MnO_2 (1% charge wt), NiO or Cu_2O *NB*: Not charcoal		Deoxidation Si 0.5–2.0% dependent on % Ni Mg 0.03–0.06% dependent on % Ni e.g. for 30% Ni alloy 1.2% Mn followed by 0.6% Si followed by 0.03% Mg Can degas with N_2 or dry air
Cast-irons			Acid cupola: Limestone 28–32 kg tonne^{-1} providing (a) Standard cupola practice (b) Coke ash content–10% (c) $CaCO_3$ is 96% of limestone 'Energized' flux for increased efficiency 21 kg tonne^{-1} (14 kg limestone + 7 kg CaF_2) Basic cupola: 80 to 90 kg tonne^{-1} of flux made up as Limestone 30–40% coke wt Dolomite 10% coke wt * Fluorspar 25% of limestone

* Can replace fluorspar by 50:50 fluorspar-soda ash.

Special purpose fluxes and inoculants

Grain refinement not usually beneficial with these alloys–encourages 'layer porosity'–although has been achieved with 0.03% Zr + 0.02% B, Ti, Co

Grain refinement of manganese bronzes by iron

Fe in alloy acts as a grain-refincr

—

Some grain refinement with Mn

—

Anhydrous soda ash or calcium carbide for desulphurization of acid cupola metal
Calcium silicide: 'Mcehanite iron'
Ferro–silicon (+1–2% Al and up to 1% Ca), zirconium etc., } for grain size control (eutectic cells) and reduction of 'chill depth'
75% FeSi (Al and Ca free) and 1–4% Sr
↓
elimination of 'pinholing' in green sand moulds

Nodularization (spheroidization): sulphur ≤0.02%
Magnesium for hypo- and hypereutectic irons introduced as: Mg impregnated coke
Mg–Ni(Si) alloys
Mg–FeSi alloys
Mg–Si alloys

Cerium for hypereutectic irons introduced as mischmetal

26.3 Aluminium casting alloys

Table 26.22 ALUMINIUM-SILICON ALLOYS

Specification BS 1490: 1988 *Related British Specifications*	LM6M(Ge) BS L33	LM20M(Ge)	LM9M(SP)	LM9TE(SP)	LM9TE(SP)	LM13TE(SP)	LM13TF(SP)	LM13TF7(SP)
Composition (%) (single figure indicates maximum)								
Copper	0.1	0.4		0.1			0.7–1.5	
Magnesium	0.1	0.2–0.6		0.2			0.8–1.5	
Silicon	10.0–13.0	10.0–13.0		10.0–13.0			10.0–12.0	
Iron	0.6	1.0		0.6			1.0	
Manganese	0.5	0.5		0.3–0.7			0.5	
Nickel	0.1	0.1		0.1			1.5	
Zinc	0.1	0.2		0.1			0.5	
Lead	0.1	0.1		0.1			0.1	
Tin	0.05	0.1		0.05			0.1	
Titanium	0.2	0.2		0.2			0.2	
Other	–	–		–			–	
Properties of material								
Suitability for:								
Sand casting	E	E*		G			G	
Chill casting (gravity die)	E	E		E			G	
Die casting (press die)	G	G		G*			F*	
Strength at elevated temperature	P	P		G			E	
Corrosion resistance	E	G		E			G	
Pressure tightness	E	E		G			F	
Fluidity	E	E		G			G	
Resistance to hot shortness	E	E		E			E	
Machinability	F	F		F			F	
Melting range, °C	565–575	565–575		550–575			525–560	
Casting temperature range, °C	710–740	680–740		690–740			680–760	
Specific gravity	2.65	2.68		2.68			2.70	

Heat treatment								
Solution temperature, °C	–	–	..	..	520–535	–	515–525	515–525
Solution time, h	–	–	–	–	2–8	–	8 (minimum)	8 (minimum)
Quench	–	–	–	–	Cold water	–	Water, 70–80 °C	Water, 70–80 °C
Precipitation temperature, °C	–	–	–	150–170	150–170	160–180	160–180	For pistons:
Precipitation time, h	–	–	–	16 (minimum)	16 (minimum)	4–16	4–16	200–250
Stabilization temperature, °C	–	–	–	–	–	–	–	4–6**
Stabilization time, h	–	–	–	–	–	–	–	
Special properties	Suitable for thin and intricate castings, readily welded	Pressure casting alloy	Suitable for low-pressure casting High strength and hardness			Low coefficient of expansion Good bearing properties Piston alloy		
Mechanical properties – sand cast – SI units (Imperial units in brackets)								
Tensile stress min., MPa (tonf in^{-2})	160(10.4)	–	–	170(11.0)	240(15.5)	–	170(11.0)	140(9.1)
Elongation min. %	5	–	–	1.5	0–1	–	0.5	1
Expected 0.2% proof stress,	60–70	–	–	110–130	220–250	–	160–190	130(8.4)
MPa (tonf in^{-2})	(3.9–4.5)	–	–	(7.1–8.4)	(14.2–16.2)		(10.4–12.3) HB 100–150	HB 65–85
Mechanical properties – chill cast – SI units (Imperial units in brackets)								
Tensile stress min., MPa (tonf in^{-2})	190(12.3)	190(12.3)	190(12.3)	230(14.9)	295(19.1)	210(13.6)	280(18.1)	200(12.9)
Elongation, min. %	7	5	3	2	0–1	1	1	1
Expected 0.2% proof stress,	70–80	70–80	75–85	150–170	270–280	–	270–300	190(12.3)
MPa (tonf in^{-2})	(4.5–5.2)	(4.5–5.2)	(4.9–5.5)	(9.7–11.0)	(17.5–18.1)	HB90–120	(17.5–19.4) HB 100–159	HB 65–85

* Not normally used in this form.

† If Ti alone is used for grain refinement then Ti ≯ 0.05%.

‡ Fully heat-treated.

§ Refine with phosphorus – subject to examination under microscope.

** Or for such time to give required BHN.

Notes

Association of Light Alloy Refiners and Smelters Grading;

E-Excellent, F-Fair, G-Good, P-Poor, U-Unsuitable,

(Ge-General purpose alloy; SP-Special purpose alloy as per BS 1490: 1988).

Table 26.22 ALUMINIUM-SILICON ALLOYS – *continued*

Specification BS 1490: 1988 *Related British Specifications*	LM18M(SP)	LM25M(Ge)	LM25TE(Ge)	LM25TB7(Ge)	LM25TF(Ge)	LM29TE(SP)	LM29TF(SP)
Composition % (Single figure indicates maximum)							
Copper	0.1	0.20				0.8–1.3	
Magnesium	0.1	0.20–0.60				0.8–1.3	
Silicon	4.5–6.0	6.5–7.0				22–25	
Iron	0.6	0.5				0.7	
Manganese	0.5	0.3				0.6	
Nickel	0.1	0.1				0.8–1.3	
Zinc	0.1	0.1				0.2	
Lead	0.1	0.1				0.1	
Tin	0.05	0.95				0.1	
Titanium	0.2	0.2†				0.2	
Other	–	–				Cr 0.6; Co 0.5, P§	
Properties of material							
Suitability for:							
Sand casting	G	G				P	
Chill casting (gravity die)	G	E				F	
Die casting (press die)	G*	G*				U	
Strength at elevated temperature	P	G‡				G	
Corrosion resistance	E	E				G	
Pressure tightness	E	G				G	
Fluidity	G	G				F	
Resistance to hot shortness	E	G				E	
Machinability	F	F				P	
Melting range, C	565–625	550–615				520–770	
Casting temperature range, °C	700–740	680–740				At least 830	
Specific gravity	2.69	2.68				2.65	

Heat treatment							
Solution temperature, °C	–	–	–	525–545	525–545	–	495–505
Solution time, h	–	–	–	4–12	4–12	–	4
Quench	–	–	–	Water, 70–80 °C	Water, 70–80 °C	–	Air blast
Precipitation temperature, °C	–	–	155–175	–	155–175	185	185
Precipitation time, h	–	–	8–12	–	8–12	To produce HB requirement	8
Stabilization temperature, °C	–	–	–	250	–	–	–
Stabilization time, h	–	–	–	2–4	–	–	–
Special properties	Readily welded		General purpose high-strength casting alloy			More suited to chill (grav. die) casting Piston alloy	
Mechanical properties – sand cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	120(7.8)	130(8.4)	150(9.7)	160(10.4)	230(149)	120(7.8)	120(7.8)
Elongation min. %	3	2	1	2.5	0–2	0.3	0.3
Expected 0.2% proof stress, MPa (tonf in^{-2})	55–60(3.6–3.9)	80–100(5.2–6.5)	120–150(7.8–9.7)	80–110(5.2–6.5)	200–250(12.9–16.2)	120(7.8) HB 100–140	120(7.8) HB 100–140
Mechanical properties – chill cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	140(9.1)	160(10.4)	190(12.3)	230(14.9)	280(18.1)	190(12.3)	190(12.3)
Elongation, min. %	4	3	2	5	2	0.3	0.3
Expected 0.2% proof stress, MPa (tonf in^{-2})	60–70(3.9–4.5)	80–100(5.2–6.5)	130–200(8.4–12.9)	90–110(5.8–7.1)	220–260(14.2–16.8)	170(11.0) HB 100–140	170–190(11.0–12.3) HB 100–140

* Not normally used in this form.

† If Ti alone is used for grain refinement then Ti ≯ 0.05%.

‡ Fully heat-treated.

§ Refine with phosphorus – subject to examination under microscope.

** Or for such time to give required BHN.

Note

E-Excellent, F-Fair, G-Good, P-Poor, U-Unsuitable.

(Ge-General purpose alloy; SP-Special purpose alloy as per BS: 1490: 1988.

Table 26.23 ALUMINIUM-SILICON-COPPER ALLOYS

Specification BS 1490:1988 *Related British Specifications*	LM2M(Ge)	LM4M(Ge)	LM4MTF (Ge)	LM16TB (SP)	LM16TF (SP) 3L78	LM21M(SP)
Composition % (Single figures indicate maximum)						
Copper	0.7–2.5	2.0–4.0		1.0–1.5		3.0–5.0
Magnesium	0.30	0.15		0.4–0.6		0.1–0.3
Silicon	9.0–11.5	4.0–6.0		4.5–5.5		5.0–7.0
Iron	1.0	0.8		0.6		1.0
Manganese	0.5	0.2–0.6		0.5		0.2–0.6
Nickel	0.5	0.3		0.25		0.3
Zinc	2.0	0.5		0.1		2.0
Lead	0.3	0.1		0.1		0.2
Tin	0.2	0.1		0.05		0.1
Titanium	0.2	0.2		0.2*		0.2
Properties of material						
Suitability for:						
Sand casting	G†	G		G		G
Chill casting (gravity die)	G†	G		G		G
Die casting (press die)	E	G		F†		G†
Strength at elevated temp.	G‡	G		G		G
Corrosion resistance	G	G		G		G
Pressure tightness	G	G		G		G
Fluidity	G	G		G		G
Resistance to hot shortness	E	G		G		G
Machinability	F	G		G		G
Melting range, °C	525–570	525–625		550–620		520–615
Casting temperature range, °C	–	700–760		690–760		680–760
Specific gravity	2.74	2.73		2.70		2.81
Heat treatment						
Solution temperature, °C	–	–	505–520	520–530	520–530	–
Solution time, h	–	–	6–16	12 (min)	12 (min)	–
Quench	–	–	Water at 70–80 °C	Water at 70–80 °C	Water at 70–80 °C	–
Precipitation temperature, °C	–	–	150–170	–	160–170	–
Precipitation time, h	–	–	6–18	–	8–10	–
Special properties	Alloy for pressure die castings	General engineering alloy Can tolerate relatively high static loading in TF condition		Pressure tight. High strength alloy in TF condition		Equally suited to all casting processes
Mechanical properties – sand cast – SI units (Imperial units in brackets)						
Tensile stress min. MPa (tonf in^{-2})	–	140(9.1)	230(14.9)	170(11.0)	230(14.9)	150(9.7)
Elongation min. %	–	2	–	2	–	1
Expected 0.2% proof stress, MPa (tonf in^{-2})	–	70–110 (4.5–7.1)	200–250 (12.9–16.2)	120–140 (7.8–9.1)	220–280 (14.2–18.1)	80–140 (5.2–9.1)
Mechanical properties – chill cast – SI units (Imperial units in brackets)						
Tensile strength min. MPa (tonf in^{-2})	150(9.7)	160(10.4)	280(18.1)	230(14.9)	280(18.1)	170(11.0)
Elongation min. %.	1	2	1	3	–	1
Expected 0.2% proof stress, MPa (tonf in^{-2})	90-130 (5.8–8.4)	80–110 (5.2–7.1)	200–300 (12.9–19.4)	140–150 (9.1–9.7)	250–300 (16.2–19.4)	80–140 (5.2–9.1)

* 0.05% min. if Ti alone used for grain refinement.
† Not normally used in this form.
‡ The use of die castings is usually restricted to only moderately elevated temperatures.

Table 26.23 ALUMINIUM-SILICON-COPPER ALLOYS – *continued*

Specification BS 1490:1988 *Related British Specifications*	LM22TB (SP)	LM24M (Ge)	LM26TE (SP)	LM27M (Ge)	LM30M (SP)	LM30TS (SP)
Composition % (Single figures indicate maximum)						
Copper	2.8–3.8	3.0–4.0	2.0–4.0	1.5–2.5	4.0–5.0	
Magnesium	0.05	0.1	0.5–1.5	0.3	0.4–0.7	
Silicon	4.0–6.0	7.5–9.5	8.5–10.5	6.0–8.0	16–18	
Iron	0.6	1.3	1.2	0.8	1.1	
Manganese	0.2–0.6	0.5	0.5	0.2–0.6	0.3	
Nickel	0.15	0.5	1.0	0.3	0.1	
Zinc	0.15	3.0	1.0	1.0	0.2	
Lead	0.1	0.3	0.2	0.2	0.1	
Tin	0.05	0.2	0.1	0.1	0.1	
Titanium	0.2	0.2	0.2	0.2	0.2	
Properties of material						
Suitability for:						
Sand casting	G†	F†	G	G	U	
Chill casting (gravity die)	G	F†	G	E	F	
Die casting (press die)	G†	E	F†	G†	G	
Strength at elevated temp.	G	G‡	E	G	G	
Corrosion resistance	G	G	G	G	G	
Pressure tightness	G	G	F	G	F	
Fluidity	G	G	G	G	G	
Resistance to hot shortness	G	G	F	G	F	
Machinability	G	F	F	G	P	
Melting range, °C	525–625	520–580	520–580	525–605	505–650	
Casting temperature range, °C	700–740	–	670–740	680–740	Well above 650°C	
Specific gravity	2.77	2.79	2.76	2.75	2.73	
Heat treatment						
Solution temperature, °C	515–530	–	–	–	–	
Solution time, h	6–9	–	–	–	–	
Quench	Water at 70–80 °C	–	–	–	–	
						Stress relief
Precipitation temperature, °C	–	–	200–210	–	–	175–225
Precipitation time, h	–	–	7–9	–	–	8(minimum)
Special Properties	Chill casting alloy (grav. die)	Alloy for pressure die castings	Piston alloy, retains strength and hardness at elevated temps.	Excellent castability	Alloy for pressure die casting automobile engine cylinder blocks	
Mechanical properties – sand cast – SI units (Imperial units in brackets)						
Tensile stress min., MPa (tonf in^{-2})	–	–	–	140(9.1)	–	–
Elongation min. %	–	–	–	1	–	–
Expected 0.2% proof stress, MPa (tonf in^{-2})	–	–	–	80–90 (5.2–5.8)	–	–
Mechanical properties – chill cast – SI units (Imperial units in brackets)		HB = 90–120				
Tensile strength min. MPa (tonf in^{-2})	245(15.9)	180(11.7)	210(13.6)	160(10.4)	150(9.7)	160(10.4)
Elongation min. %	8	1.5	1	2	0.5	0.5
Expected 0.2% proof stress, MPa (tonf in^{-2})	110–120 (7.1–7.8)	100–120 (6.7–7.7)	160–190 (10.4–12.3)	90–110 (5.8–7.1)	150–200 (9.7–12.9)	160–200 (10.4–12.9)

Notes
E-Excellent, F-Fair, G-Good, P-Poor, U-Unsuitable.
Numerical purpose alloy; Sp-Special purpose alloy as per BS 1490: 1970).

Table 26.24 ALUMINIUM-COPPER ALLOYS

Specification BS 1490:1988	LM12M(SP)	LM12TF(SP)*	[LM14-WP]†	[LM11-W]	[LM11-WP]	–	–
Aerospace							
BSL series	–	–	4L35	2L91	2L92	–	–
DTD series	–	–	–	–	–	361B	741A
Composition % (Single figures indicate maximum)							
Copper	9.0–11.0		3.5–4.5	4.0–5.0		4.0–5.0	3.5–4.5
Magnesium	0.2–0.4		1.2–1.7	0.10		0.10	1.2–2.5
Silicon	2.5		0.6‡	0.25		0.25	0.5
Iron	1.0		0.6‡	0.25		0.25	0.5
Manganese	0.6		0.6	0.10		0.10	0.1
Nickel	0.5		1.8–2.3	0.10		0.10	0.1
Zinc	0.8		0.1	0.10		0.10	0.1
Lead	0.1		0.05	0.05		0.05	0.1
Tin	0.1		0.05	0.05		0.05	0.05
Titanium	0.2		0.25	0.25		Ti + Nb 0.05–0.30	–
Other	–		–	–		–	Co 0.5–1.0 Nb 0.05–0.3
Properties of material							
Suitability for:							
Sand casting	F		F	F		F	F
Chill casting (gravity die)	G		G	P		P	G
Die casting (press die)	U		U	U		–	
Strength at elevated temperature	G		E	F		–	–
Corrosion resistance	P		F	F		F	F
Pressure tightness	G		E	P		P	F
Fluidity	F		G	F		F	G
Resistance to hot shortness	G		G	P		P	G
Machinability	E		G	G		G	G
Melting range, °C	525–625		530–640	545–640		540–640	530–640
Casting temperature range, °C	700–760		700–750	680–700		675–750	710–725
Specific gravity	2.94		2.82	2.80		2.80	2.80

Heat treatment							
Solution temp., °C	–	515–520	500–520	525–545	525–545	525–545	495–505
Solution time, h	–	6	6	12–16	12–16	16 (minimum)	10 (minimum)††
Quench		Water at 70–80 °C	Boiling water	Water at 70–80 °C	Water at 70–80 °C	Water or oil	Oil at 80–90 °C
Precipitation temperature, °C	–	175–180	95–103§	120–140	120–170	160–70	195–205
Precipitation time, h	–	2 (*minimum*)	2**	1–2	12–14	8–16	4–5
Special properties	Piston alloy, now superseded by LM13 and LM26. Excellent machinability		Excellent props. at elevated temperatures Grav. die alloy	Good shock resistance		High strength alloy	
Mechanical properties – sand cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	–	–	220 (14.2)	220 (14.2)	280 (18.1)	324 (21.0)	263 (17.0)
Elongation %	–	–	–	7	4	–	–
Expected 0.2% proof stress, min., MPa (tonf in^{-2})	–	–	210–240 (13.6–15.5)	165–200 (10.7–12.9)	200–240 (12.9–15.5)	310 (20.1)	250 (16.2)
Mechanical properties – chill cast – SI units (Imperial units in brackets)							
Tensile stress min., MPa (tonf in^{-2})	170	278 (18.0)	280 (18.1)	265 (17.1)	310 (20.1)	402 (26.0)	340 (22.0)
Elongation %	–	–	–	13	9	4	–
Expected 0.2% proof stress, min., MPa (tonf in^{-2})	140–170	139–170 (9.0–11.0) HB 100–150	230–260 (14.9–16.8) HB 100–130	165–200 (10.7–12.9)	200–240 (12.5–15.5)	360 (23.3)	260 (16.8)

* Not included in BS 1490:1988.
†[] signifies obsolete specification:
‡ Si + Fe 1.0 max.
§ Or 5 days ageing at room temp.
** Can substitute stabilizing treatment at 200–250 °C if used for pistons.
†† Allow to cool to 480 °C before quench.

Note:
E-Excellent. F-Fair. G-Good. P-Poor. U-Unsuitable.
(Ge-General purpose alloy; SP-Special purpose alloy as per BS 1490:1988).

Table 26.25 MISCELLANEOUS ALUMINIUM ALLOYS

Specification BS 1400:1988	LM5M(SP)	–	LM10TB(SP)	–
Aerospace				
BSL series	–	–	4L53	L99
DTD series	–	5018A	–	–
Composition % (Single figures indicate maximum)				
Copper	0.1	0.2	0.1	0.1
Magnesium	3.0–6.0	7.4–7.9	9.5–11.0	0.20–0.45
Silicon	0.3	0.25	0.25	6.5–7.5
Iron	0.6	0.35	0.35	0.20
Manganese	0.3–0.7	0.1–0.3	0.10	0.10
Nickel	0.1	0.1	0.10	0.10
Zinc	0.1	0.9–1.4	0.10	0.10
Lead	0.05	0.05	0.05	0.05
Tin	0.1	0.05	0.05	0.05
Titanium	0.2	0.25	0.2†	0.20
Other	–	–	–	–
Properties of material				
Suitability for:				
Sand casting	F	F	F	G
Chill casting (gravity die)	F	F	F	E
Die casting (press die)	F‡	–	F‡	F‡
Strength at elevated temp.	F	F	F	–
Corrosion resistance	E	E	E	E
Pressure tightness	P	P	P	G
Fluidity	F	F	F	G
Resistance to hot shortness	F	G	G	G
Machinability	G	G	G	F
Melting range °C	580–642	–	450–620	550–615
Casting temperature range, °C	680–740	680–720	680–720	680–740
Specific gravity	2.65	2.64	2.57	2.67
Heat treatment				
Solution temperature, °C	–	425–435§	425–435	535–545
Solution time, h	–	8	8	12
Quench	–	Oil at 160 °C** or boiling water	Oil at no more†† than 160 °C	Water at 65 °C min
Precipitation temp., °C	–	–	–	150–160
Precipitation time, h	–	–	–	4
Special properties	Good corrosion resistance in marine atmospheres	–	Good shock resistance and high corrosion resistance ***	Excellent castability with good mech. props.
Mechanical properties – sand cast – SI units (Imperial units in brackets)				
Tensile stress min, MPa (tonf in^{-2})	140 (9.1)	278	280 (18.0)	230 (14.9)
Elongation %	3	3	8	2
Expected 0.2% proof stress, min MPa (tonf in^{-2})	90–110 (5.8–7.1)	170 (11.0)	170–190 (11.0–12.3)	185 (12.0)
Mechanical properties – chill cast – SI units (Imperial units in brackets)				
Tensile stress min, MPa (tonf in^{-2})	170 (11.0)	309 (20.0)	310 (20.1)	280 (18.1)
Elongation %	5	10	12	5
Expected 0.2% proof stress, min MPa (tonf in^{-2})	90–120 (5.8–7.8)	170 (11.0)	170–200 (11.0–12.9)	200 (12.9)

* [] obsolete.
† 0.05% min, if Ti alone used for grain refinement.
‡ Not normally used in this form.
§ Or 8 h 435–445 °C then raise to 490–500 °C for further 8 h and quench as in table.
** Do not retain castings in oil for more than 1 h.
*** Not generally recommended since occasional brittleness can develop over long periods.

Table 26.25 MISCELLANEOUS ALUMINIUM ALLOYS – *continued*

Specification BS 1400:1988 *Aerospace*	LM28TE(SP)	LM28TF(SP)	[LM23P]*	[LM15WP]*	–
BSL series	–	–	3L51	3L52	–
DTD series	–	–	–	–	5008B
Composition % (Single figures indicate maximum)					
Copper		1.3–1.8	0.8–2.0	1.3–3.0	0.1
Magnesium		0.8–1.5	0.05–0.2	0.5–1.7	0.5–0.75
Silicon		17–20	1.5–2.8	0.6–2.0	0.25
Iron		0.7	0.8–1.4	0.8–1.4	0.5
Manganese		0.6	0.1	0.1	0.1
Nickel		0.8–1.5	0.8–1.7	0.5–2.0	0.1
Zinc		0.2	0.1	0.1	4.8–5.7
Lead		0.1	0.05	0.05	0.1
Tin		0.1	0.05	0.05	0.05
Titanium		0.2	0.25	0.25	0.15–0.25
Other		Cr 0.6 Co 0.5	–	–	Cr 0.4–0.6
Properties of material					
Suitability for:					
Sand casting		P	G	F	F
Chill casting (gravity die)		F	G	G	P
Die casting (press die)		–	G‡	U	U‡
Strength at elevated temp.		F	G	E	F
Corrosion resistance		G	G	G	E
Pressure tightness		F	G	F	F
Fluidity		F	F	F	F
Resistance to hot shortness		G	G	G	P
Machinability		P	G	G	G
Melting range °C		520–675	545–635	600–645	572–615
Casting temperature range, °C		≯735	680–750	685–755	730–770
Specific gravity		2.68	2.77	2.75	2.81
Heat treatment					
Solution temperature, °C	–	495–505	–	520–540	–
Solution time, h	–	4	–	4	–
Quench	–	Air blast	–	Water at 80–100 °C Oil or air blast	–
Precipitation temp., °C	185	185	150–175	150–180 (195–205)	175–185‡‡ (at least 24 h after cast)
Precipitation time, h	To produce required HB	8	8–24	8–24 (2–5)	10 (at least 24 h after cast)
Special properties	Piston alloy		Aircraft engine castings	High mechanical props. at elevated temps.	Good strength without heat treatment. *See*‡‡
Mechanical properties – sand cast – SI units (Imperial units in brackets)					
Tensile stress min, MPa (tonf in^{-2})	–	120 (7.8)	160 (10.4)	280 (18.1)	216 (14.0)
Elongation %	–	–	2	–	4
Expected 0.2% proof stress, min MPa (tonf in^{-2})	–	– HB 100–140	125 (8.1)	245 (15.9)	150 (9.7)
Mechanical properties – chill cast – SI units (Imperial units in brackets)					
Tensile stress min, MPa (tonf in^{-2})	170 (11.0)	190 (12.3)	200 (13.0)	325 (21.0)	232 (15.0)
Elongation %	–	–	3	–	5
Expected 0.2% proof stress, min MPa (tonf in^{-2})	– HB 90–130	160–190 (10.4–12.3) HB 100–140	140 (19.1)	295 (19.1)	180 (11.7)

* Can be furnace cooled to 385–395 °C before quench. Do not retain in oil for more than 1 h. Further quench in water or air. Alternative – room temp. age-harden for 3 weeks.

Note:
E-Excellent, F-Fair. G-Good. P-Poor. U-Unsuitable.
Ge-General purpose alloy; SP-Special purpose alloy as per BS 1490:1988).

Table 26.26a HIGH STRENGTH CAST Al ALLOYS BASED ON Al–4.5 Cu

European Designation	KO1				A–U5GT					
Al Assoc (USA) designation	201.0	201.2	A201.0	A201.2	204.0	204.2	206.0	206.2	A206.0	A206.2
Cu	4.0–5.2	4.0–5.2	4.0–5.0	4.0–5.0	4.2–5.0	4.2–4.9	4.2–5.0	4.2–5.0	4.2–5.0	4.2–5.0
Mg	0.15–0.55	0.20–0.55	0.15–0.35	0.20–0.35	0.15–0.35	0.20–0.35	0.15–0.35	0.20–0.35	0.15–0.35	0.20–0.35
Si	0.10	0.10	0.05	0.05	0.20	0.15	0.10	0.10	0.05	0.05
Fe	0.15	0.10	0.10	0.07	0.35	0.10–0.20	0.15	0.10	0.10	0.07
Mn	0.20–0.50	0.20–0.50	0.20–0.40	0.20–0.40	0.10	0.05	0.20–0.50	0.20–0.50	0.20–0.50	0.20–0.50
Ni	—	—	—	—	0.05	0.03	0.05	0.03	0.05	0.03
Zn	—	—	—	—	0.10	0.05	0.10	0.05	0.10	0.05
Sn	—	—	—	—	0.05	0.05	0.05	0.05	0.05	0.05
Ti	0.15–0.35	0.15–0.35	0.15–0.35	0.15–0.35	0.15–0.30	0.15–0.25	0.15–0.3	0.15–0.25	0.15–0.30	0.15–0.25
Ag	0.40–1.0	0.40–1.0	0.40–1.0	0.40–1.0	—	—	—	—	—	—
Others each	0.05	0.05	0.03	0.03	0.05	0.05	0.05	0.05	0.05	0.05
Others total	0.10	0.10	0.10	0.10	0.15	0.15	0.15	0.15	0.15	0.15

Table 26.26b MINIMUM REQUIREMENTS FOR SEPARATELY CAST TEST BARS

Alloy	*Sand/Die*	*Treatment**	*UTS* MPa	0.2*PS* MPa	*El* % *in 50 mm or 4 × diam*	*Typical HB* 500 kgf 10 mm
201.0	Sand	T6	414	345	5.0	110–140
	Sand	T7	414	345	3.0	130
204.0	Sand	T4	311	194	6.0	95
	Die	T4	331	220	8.0	

* For temper designations see Table 29.13

Table 26.26c TYPICAL PROPERTIES OF SEPARATELY CAST TEST BARS

Alloy	*Sand/Die*	*Treatment**			*UTS* MPa	0.2*PS* MPa	*El* % *in 50 mm or 4 × diam*	*Typical HB* 500 kgf 10 mm
201.0	Sand	T4			365	215	20	95
		T43			414	255	17	
	Sand	T6			448–485	380–435	7–8	135
	Sand	T7	Room	Temp.	460–469	415	4.5–5.5	130
		T7	150C*	0.5–100 h	380	360	6–8.5	
				1 000 h	360	345	8	
				10 000 h	315	275	7	
			205C	0.5 h	325	310	9	
				100 h	285	270	10	
				1 000 h	250	230	9	
				10 000 h	185	150	14	
			260C	0.5 h	195	185	14	
				100 h	150	140	17	
				1 000 h	125	110	18	
			315C	0.5 h	140	130	12	
				100 h	85	75	30	
				1 000 h	70	60	39	
				10 000 h	60	55	43	
A206.0	Sand	T4						118 HV
		T7		20C	436	347	11.7	137 HV
				120C	384	316	14.0	
				175C	333	302	17.7	

* Elevated temperature properties.

26.4 Copper base casting alloys

Table 26.27 GUNMETALS

Alloy	*Gunmetal* 88/10/2	*Nickel gunmetal* (*as cast*)	*Nickel gunmetal** (*fully heat treated*)
Specification BS 1400:1969	G1	G3	G3WP
Alloy grouping†	C	C	C
Composition % (Single figures indicate maximum)			
Tin	9.5–10.5		6.5–7.5
Zinc	1.75–2.75		1.5–3.0
Lead	1.5		0.10–0.50
Nickel	1.0		5.25–5.75
Silicon	0.02		0.01
Bismuth	0.03		0.02
Aluminium	0.01		0.01
Iron + arsenic + antimony	0.20		0.20
Manganese	—		0.20
Total impurities	0.50		0.50
Properties of material			
Suitability for:			
Sand casting	2§		2
Chill casting	3		3
Die casting (gravity)	3		3
Centrifugal	2		2
Continuous	1		2
Pressure tightness for sand castings:			
Thin sections	2**		1
Thick sections	2		1
Machining	2§§		2
Resistance to corrosion	All these alloys withstand atmospheric natural water and sea water corrosion to a degree depending largely upon the tin content (88/10/2 best)		
Fluidity	Addition of phosphorus in amounts of order of 0.05% for deoxidation gives high fluidity in all cases		
Hot shortness	All alloys are very hot short		
Bearing properties	All alloys suitable for bearing applications—choice dependent on conditions		
Density (g cm^{-3})	8.8		8.8
Casting temperature range, °C			
Under 13 mm section	1 200		1 080–1 200
13–39 mm section	1 170		
Over 40 mm section	1 130		
Mechanical properties—SI units (Imperial units in brackets) in order sand cast, chill cast, continuously cast, centrifugally cast†† (BS 1400)			
Tensile stress min,			
MPa	270, 230, 300, 250	280, —, 340, —	430, —, 430, —
(tonf in^{-2})	(17.5, 14.9, 19.4, 16.2)	(18.1, —, 22.0, —)	(27.8, —, 27.8, —)
0.2% proof stress min			
MPa	130, 130, 140, 130	140, —, 170, —	280, —, 280, —
(tonf in^{-2})	(8.4, 8.4, 9.1, 8.4)	(9.1, —, 11.0, —)	(18.1, —, 18.1, —)
Elongation $5.65\sqrt{S_0}$%	13, 3, 9, 5	16, —, 18, —	3, —, 3, —
			HB 160 min

* Heat treatment 2 h at 790 ± 10 °C air cool plus 6 h at 320 ± 10 °C air cool.
† Group A alloys in common use; group B special purpose alloys; group C alloys in limited production.
‡ Tin + ½ Nickel content 7.0–8.0%.
§ Grading 1 = Excellent.
2 = Satisfactory.
3 = Possible with special techniques.
4 = Unsuitable.
5 = Not applicable.
** Grading 1 = Suitable
2 = Less suitable.
3 = Unsuitable.
†† Values apply to samples cut from centrifugal castings made in metallic moulds. Min. props. of centrifugal castings made in sand moulds same as for other sand castings.

Table 26.27 GUNMETALS—*continued*

Alloy	*Leaded gunmetal* 83/3/9/5	*Leaded gunmetal* 85/5/5/5	*Leaded gunmetal* 87/7/3/3	*Leaded semi-red brass* 76/3/6/15
Specification				
BS 1400:1969	LG1	LG2	LG4	– –
Alloy grouping †	B	A	A	A
Composition % (Single figures indicate maximum)				
Tin	2.0–3.5	4.0–6.0	6.0–8.0‡	2.5–3.5
Zinc	7.0–9.5	4.0–6.0	1.5–3.0	13.0–17.0
Lead	4.0–6.0	4.0–6.0	2.5–3.5	5.25–6.75
Nickel	2.0	2.0	2.0‡	1.0
Silicon	0.02	0.02	0.01	0.01
Bismuth	0.10	0.05	0.05	– –
Aluminium	0.01	0.01	0.01	–
Iron + arsenic + antimony	0.75	0.50	0.40	0.55
Manganese		—	—	—
Total impurities	1.0	0.80	0.70	—
Properties of material				
Suitability for:				
Sand casting	1	1	1	1
Chill casting	2	2	2	2
Die casting (gravity)	3	3	3	3
Centrifugal	2	1	1	2
Continuous	2	1	1	2
Pressure tightness for sand castings:				
Thin sections	1	1	2	2
Thick sections	2	2	1	2
Machining	1	1	1	2
Resistance to corrosion	All these alloys withstand atmospheric natural water and sea water corrosion to a degree depending largely upon the tin content (88/10/2 best)			
Fluidity	Addition of phosphorus in amounts of order of 0.05% for deoxidation gives high fluidity in all cases			
Hot shortness	All alloys are very hot short			
Bearing properties	All alloys suitable for bearing applications—choice dependent on conditions			
Density (g cm^{-3})	8.8	8.8	8.8	8.77
Casting temperature range °C				
Under 13 mm section	1 180	1 200	1 200	1 150–1 260
13–39 mm section	1 140	1 150	1 160	1 110–1 220
Over 40 mm section	1 100	1 120	1 120	1 066–1 177
Mechanical properties – SI units (Imperial units in brackets) in order sand cast, chill cast, continuously cast, centrifugally cast†† (BS 1400)				
Tensile stress min MPa	180, 180, –, –	200, 200, 270, 220	250, 250, 300, 250	Sand cast 172
(tonf in^{-2})	(11.7, 11.7, —, —)	(13.0, 13.0, 17.5, 13.0)	(16.2, 16.2, 19.4, 16.2)	(Sand cast 11.6)
0.2% proof stress min, MPa	80, –, —, —	100, 110, 100, 110	130, 130, 130, 130	0.5% proof stress sand cast 83
(tonf in^{-2})	(5.2, —, —, —)	(6.5, 7.1, 6.5, 7.1)	(8.4, 8.4, 8.4, 8.4)	(Sand cast 5.4)
Elongation $5.65\sqrt{S_o}$%	11.2, —, —	13, 6, 13, 8	16, 5, 13, 6	Sand cast 15 (50.8 mm GL)

† Grading 1 = Excellent
2 = Good
3 = Satisfactory with special techniques
(Comparison between copper alloys rather than with other metals)

Table 26.28 BEARING BRONZES

Alloy	*Phosphor bronze*	*Phosphor bronze for gear blanks*	*Phosphor bronze*	*Phosphor bronze*	*Leaded phosphor bronze*
Specification BS 1400: 1985	PB1	PB2	CT1	PB4	LPB1
Alloy grouping†	B	B	B	A	A
Composition % (Single figures indicate maximum unless otherwise stated)					
Tin	10.0 min	11.0–13.0	9.0–11.0	9.5 min	6.5–8.5
Phosphorus	0.50 min	0.15 min	0.15 max	0.40 min	0.30 min
Lead	0.25	0.50	0.25	0.75	2.0–5.0
Zinc	0.05	0.30	0.05	0.50	2.0
Nickel	0.10	0.50	0.25	0.50	1.0
Iron	0.10	0.15	—	—	—
Silicon	0.02	0.02	—	—	—
Aluminium	0.01	0.01	—	—	—
Total impurities	0.60	0.20	0.80	0.50	0.50
Copper	REM	REM	REM	REM	REM
Properties of material					
Suitability for:					
Sand casting	2‡	2	2	2	2
Chill casting	1	1	1	1	1
Die casting (gravity)	3	3	3	3	3
Centrifugal	1	1	1	1	2
Continuous	1	1	1	1	1
Pressure tight sand castings					
Thin sections	3§	3	2	3	2
Thick sections	3	3	3	3	2
Machining	2‡‡	2	2	2	1
Corrosion resistance	All alloys are resistant to natural and sea water				
Fluidity	Good	Good	Good	Good	Good
Hot shortness	All alloys are very hot short				
Density (g cm^{-3})	8.8	8.8	8.8	8.8	8.8
Casting temperature range, °C					
Under 13 mm section	1 120	1 170	1 100	1 120	1 130
13–39 mm section	1 100	1 120	1 070	1 100	1 050
Over 40 mm section	1 040	1 070	1 040	1 060	1 030
Mechanical properties—SI units (Imperial units in brackets) in order sand cast, chill cast, continuously cast, centrifugally cast** BS 1400					
Tensile stress (min)					
MPa	210, 310, 360, 330	220, 270, 310, 280	230, 270, 310, 280	190, 270, 330, 280	190, 220, 270, 230
(tonf in^{-2})	(13.6, 20.1, 23.3, 21.4)	(14.2, 17.5, 20.1, 18.1)	(14.9, 17.5, 20.1, 18.1)	(12.3, 17.5, 21.4, 18.1)	(12.3, 14.2, 17.5, 14.9)
0.2% proof stress (min)					
MPa	130, 170, 170, 170	130, 170, 170, 170	130, 140, 160, 140	100, 140, 160, 140	80, 130, 130, 130
(tonf in^{-2})	(8.4, 11.0, 11.0, 11.0)	(8.4, 11.0, 11.0, 11.0)	(8.4, 9.1, 10.4, 9.1)	(6.5, 9.1, 10.4, 9.1)	(5.2, 8.4, 8.4, 8.4)
Elongation on $5.65\sqrt{S_0}$%	3, 2, 6, 4	5, 3, 5, 3	6, 5, 9, 6	3, 2, 7, 4	3, 2, 5, 4

Specification B.S. 1400: 1985	LB1	LB2	LB4	LB5
Alloy grouping†	C	A	A	B
Composition % (Single figures indicate maximum unless otherwise stated)				
Tin	8.0–10.0	9.0–11.0	4.0–6.0	4.0–6.0
Phosphorus	0.10	0.10	0.10	0.10
Lead	13.0–17.0	8.5–11.0	8.0–10.0	18.0–23.0
Zinc	1.0	1.0	2.0	1.0
Nickel	2.0	2.0	2.0	2.0
Iron	Sb 0.50	Sb 0.50 Fe 0.15	Sb 0.50	Sb 0.50
Silicon	0.02	0.02	0.02	0.01
Aluminium	—	0.01	—	—
Total impurities	0.30	0.50	0.50	0.30
Copper	REM	REM	REM	REM
Properties of material				
Suitability for:				
Sand casting	3	2	2	3
Chill casting	2	1	1	2
Die casting (gravity)	4	4	4	4
Centrifugal	2	2	2	3
Continuous	1	1	1	3
Pressure tight sand castings				
Thin sections	2	2	2	2
Thick sections	3	2	2	3
Machining	1	1	1	1
Corrosion resistance	All alloys are resistant to natural and sea water			
Fluidity	Good	Good	Good	Good
Hot shortness	All alloys are very hot short			
Density (g cm^{-3})	9.1	9.0	9.0	9.2
Casting temperature range, °C				
Under 13 mm section	1 110	1 130	1 110	1 090
13–39 mm section	1 030	1 080	1 070	1 030
Over 40 mm section	1 010	1 030	1 040	1 010
Mechanical properties—SI units (Imperial units in brackets) in order sand cast, chill cast, continually cast, centrifugally cast** BS 1400				
Tensile stress (min)				
MPa	170, 200, 230, 220	190, 220, 280, 230	160, 200, 230, 220	160, 170, 190, 190
(tonf in^{-2})	(11.0, 13.0, 14.9, 14.2)	(12.3, 14.2, 18.1, 14.9)	(10.4, 13.0, 14.9, 14.2)	(10.4, 11.1, 12.3, 12.3)
0.2% proof stress (min)				
MPa	80, 130, 130, 130	80, 140, 160, 140	60, 80, 130, 80	60, 80, 100, 80
(tonf in^{-2})	(5.2, 8.4, 8.4, 8.4)	(5.2, 9.1, 10.4, 9.1)	(3.9, 5.2, 8.4, 5.2)	(3.9, 5.2, 6.5, 5.2)
Elongation on $5.65\sqrt{S_0}$%	4, 3, 9, 4	5, 3, 6, 5	7, 5, 9, 6	5, 5, 8, 7

* This bronze is now primarily intended for shaped castings rather than bearings.

† *See* footnote † to Table 26.27.

‡ *See* footnote § to Table 26.27.

§ *See* footnote** to Table 26.27.

** *See* footnote †† to Table 26.27.

†† *See* footnote §§ to Table 26.27.

Table 26.29 BRASSES

Alloy	*Brass sand cast*	*Brass sand cast*	*Naval brass sand cast*
Specification BS 1400: 1985	SCB1	SCB3	SCB4
Alloy grouping	A	A	C
Composition % (Single figures indicate maximum unless otherwise stated)			
Copper	70.0–80.0	63.0–70.0	60.0–63.0
Lead	2.0–5.0	1.0–3.0	0.5
Tin	1.0–3.0	1.5	1.0–1.5
Iron	0.75	0.75	—
Nickel	1.0	1.0	—
Aluminium	0.01	0.1	0.01
Others	—	—	—
Total impurities	1.0	1.0	0.75
Zinc	REM	REM	REM
Properties of material			
Suitability for:			
Sand casting	1‡	1	1
Chill casting	5	5	5
Die casting (gravity)	5	5	5
Centrifugal	3	3	3
Continuous	2	2	5
Pressure tight castings (sand)			
Thin sections	1§	1¶	1
Thick sections	1	1¶	1
Machining	1§§	1	2
Corrosion resistance	Generally excellent in natural waters, DCB1, DCB3, PCB1, SCB1, SCB3 undergo dezincification in sea water		
Hot shortness	Alpha brasses tend to be hot short. Alpha/beta brasses relatively good		
Density (g cm^{-3})	8.5	8.4	8.3
Casting temperature range, °C			
Under 13 mm section	1 150	1 100	1 100
13–39 mm section	1 100	1 050	1 050
Over 40 mm section	1 070	1 020	1 020
Mechanical properties—SI units (Imperial units in brackets)—sand cast props.** for alloys SCB1, 3, 4, 6—chill cast‡‡ for DCB1 and 3 and PCB1			
Tensile stress (typical)			
MPa	170–200	190–220	250–310
(tonf in^{-2})	(11.0–13.0)	(12.3–14.2)	(16.2–20.1)
0.2% proof stress (typical)			
MPa	80–110	70–110	70–110
(tonf in^{-2})	(5.2–7.1)	(4.5–7.1)	(4.5–7.1)
Elongation on $5.65\sqrt{S_0}$% (typical)	18–40	11–30	18–40

* 0.1% Pb if required.
† Nickel to be counted as copper.
‡ } *See* footnotes § and ** to Table 26.27.
§ }
¶ For pressure tight castings Al ≤ 0.02%.
** On separately cast test bars.
†† Values based on 15–40 mm thick sections from castings.
‡‡ Values based on 15–40 mm sections for DCB1, DCB3 and PCB1.
§§ *See* footnote §§ to Table 26.27.

Alloy	*Brass brazable castings*	*Brass die castings*	*Brass for diecasting*	*Brass for pressure diecasting*
Specification BS 1400:1969	SCB6	DCB1*	DCB3†	PCB1
Alloy grouping	A	A	A	A
Composition % (Single figures indicate maximum unless otherwise stated)				
Copper	83.0–86.0	59.0–63.0	58.0–63.0	57.0–60.0
Lead	0.5	0.25	0.5–2.5	0.5–2.5
Tin	--	--	1.0	0.5
Iron			0.8	0.3
Nickel		--	1.0	--
Aluminium		0.5	0.2–0.8	0.5
Others	As 0.05–0.20	--	Mn 0.5 Si 0.05	--
Total impurities	1.0 (incl. Pb)	0.75	2.0 (excl. Ni+Pb+Al)	0.5
Zinc	REM	REM	REM	REM

Table 26.29 BRASSES—*continued*

Alloy	*Brass brazable castings*	*Brass die castings*	*Brass for diecasting*	*Brass for pressure diecasting*
Specification BS 1400: 1985	SCB6	DCB1*	DCB3†	PCB1
Alloy grouping	A	A	A	A
Properties of material				
Suitability for:				
Sand casting	1	5	5	5
Chill casting	5	1	1	1
Die casting (gravity)	5	1	1	1
Centrifugal	3	2	2	2
Continuous	2	5	3	5
Pressure tight castings (sand)				
Thin sections	1	—	—	—
Thick sections	1	—	—	—
Machining	3	2	1	2
Corrosion resistance	Generally excellent in natural waters. DCB1, DCB3, PCB1, SCB1, SCB3 undergo dezincification in sea water			
Hot shortness	Alpha brasses tend to be hot short. Alpha/beta brasses relatively good			
Density (g cm^{-3})	8.6	8.3	8.3	8.3
Casting temperature range, °C				
Under 13 mm section	1 150			
13–39 mm section	1 100	1 050	1 050	Injection temp. 950
Over 40 mm section	1 070			
Mechanical properties—SI units (Imperial units in brackets)—sand cast props.,**for alloys SCB1, 3, 4, 6—chill cast‡‡ for DCB1 and 3 and PCB1				
Tensile stress (typical)				
MPa	170–190	280–370	300–340	280–370
(tonf in^{-2})	(11.0–12.3)	(18.1–24.0)	(19.4–22.0)	(18.1–24.0)
0.2% proof stress (typical)				
MPa	80–110	90–120	90–120	90–120
(tonf in^{-2})	(5.2–7.1)	(5.8–7.8)	(5.8–7.8)	(5.8–7.8)
Elongation on $5.65\sqrt{S_0}$% (typical)	18–40	23–50	13–40	25–40

Table 26.30 HIGH TENSILE BRASSES

Zinc equivalents

Guillet method		*American method*	
Element	*Coefficient*	*Element*	*Coefficient**
Silicon	10	Silicon	+10
Aluminium	6	Aluminium	+5.0
Tin	2	Tin	+1.0
Lead	1	Lead	—
Iron	0.9	Iron	−0.1
Manganese	0.5	Manganese	−0.5
Nickel	−1.2	Nickel	−2.3
Magnesium	2	Magnesium	+1.0

$$\text{Zinc equivalent} = \frac{[\%\text{Zn} + \Sigma(\%M \times \text{coeff})]100}{[\%\text{Zn} + \Sigma(\%M \times \text{coeff}) + \%\text{Cu}]}$$

$$\text{Zinc equivalent} = \left[100 - \frac{100 \times \%\text{Cu}}{100 + \Sigma(\%M \times \text{coeff})}\right]$$

Where

M = alloying element

% α-phase = 10 (46.6-zinc equivalent)

In practice, these factors operate with good accuracy, provided that the element considered is not present in amounts greater than 2%.

* These values are Guillet Coefficients minus 1.

These values are employed as a guide to whether a complex brass will have either alpha, beta, or mixed alpha/beta structure. For instance equivalent zinc values of 46.6% and above will produce a beta structure. To obtain 15% alpha the zinc equivalent must be below 45%. As further examples, 1%Si will be equivalent to 10%Zn, and 1%Ni is equivalent to takin 1.2%Zn out (i.e. putting 1.2%Cu in).

Table 26.30 HIGH TENSILE BRASSES—*continued*

Alloy	*Alpha Beta* (460 MPa†) *High tensile brass*	*All Beta* (740 MPa‡) *High tensile brass*
Specification BS 1490: 1985	HTB1§	HTB3
Alloy grouping	B	B
Composition % (Single figures indicate maximum)		
Copper	55.0 min	55.0 min
Manganese	3.0	4.0
Aluminium	0.5–2.5	3.0–6.0
Iron	0.7–2.0¶	1.5–3.25
Tin	1.0	0.20
Nickel	1.0	1.0
Lead	0.50	0.20
Silicon	0.10	0.10
Total impurities	0.20	0.20
Zinc	REM	REM
Properties of material		
Suitability for:		
Sand casting	2††	2
Chill casting	5	5
Gravity die casting	2	4
Centrifugal	2	2
Continuous	5	5
Pressure tight sand castings		
Thin sections	1‡‡	1
Thick sections	1	1
Machining	3••	3
Corrosion resistance	α/β structure–not susceptible to stress corrosion cracking	All β alloy–susceptible to stress corrosion cracking
Density (g cm^{-3})	8.3	7.9
Casting temperature range, °C		
Under 13 mm section	1 060	1 060
13–39 mm section	1 020	1 020
Over 40 mm section	980	980
Mechanical properties—SI units (Imperial units in brackets) in order sand cast, chill cast, continuously cast, centrifugally cast§§		
Tensile stress, min		
MPa	470, 500, —, 500	740, —, —, 740
(tonf in^{-2})	(30.4, 32.4, —, 32.4)	(47.9, —, —, 47.9)
0.2% proof stress, min		
MPa	170, 210, —, 210	400, —, —, 400
(tonf in^{-2})	(11.0, 13.6, —, 13.6)	(25.9, —, —, 25.9)
Elongation on $5.65\sqrt{S_0}$%min	18, 18, —, 20	11, —, —, 13

† Originally known as 30 ton HTB.
‡ Originally known as 48 ton HTB.
§ Micro-structure requirement: 15%α-phase min.
¶ For grain refinement (grain dia. 0.5 mm or less on 29 mm sand cast test bars). Optimum iron for grain refinement approx.–1.1% in HTB 1.
†† For grading *see* footnote § to Table 26.27.
‡‡ For grading *see* footnote•• to Table 26.27.
§§ Values apply to samples cut from castings made in metallic moulds.
•• *See* footnote §§ to Table 26.27.

Table 26.31 MISCELLANEOUS COPPER-BASE ALLOYS

Alloy	*Aluminium bronze*	*Aluminium bronze*	*Copper manganese aluminium*	*Copper manganese aluminium*
Specification BS 1400: 1985	AB1	AB2	CMA1	CMA2
*Alloy grouping**	B	B	B	B
Composition % (Single figures indicate maximum)				
Aluminium	8.5–10.5	8.8–10.0	7.5–8.5	8.5–9.0
Iron	1.5–3.5	4.0–5.5	2.0–4.0	2.0–4.0
Nickel	1.0	4.0–5.5	1.5–4.5	1.5–4.5
Manganese	1.0	1.5	11.0–15.0	11.0–15.0
Zinc	0.50	0.50	0.50	0.50
Silicon	0.25	0.10	0.15	0.15
Tin	0.10	0.10	1.0	1.0
Lead	0.05†	0.05†	0.05	0.05
Phosphorus	—	—	0.05	0.05
Magnesium	0.05	0.05	—	—
Chromium	—	—	—	—
Copper	REM	REM	REM	REM
Total impurities	0.30	0.30	0.30	0.30
Properties of material				
Suitability for:				
Sand casting	2‡	2	2	2
Chill casting	5	5	5	5
Gravity die casting	1	2	2	2
Centrifugal	2	2	2	2
Continuous	3	3	3	3
Pressure tight castings (sand)				
Thin sections	1§	1	1	1
Thick sections	1	1	1	1
Machining	3¶	3	3	3
Corrosion resistance	Very good except under reducing conditions**	Very good except under reducing conditions**	Very good	Very good
Fluidity	Fair	Fair	Good	Good
Strength at elevated temperatures	Very good	Excellent	Very good	Very good
Electrical conductivity % IACS at 15 °C	13	8	3	3
Density (g cm $^{-3}$)	7.6	7.6	7.5	7.5
Casting temperature range, °C				
Under 13 mm section	1 250	1 240	1 150	1 150
13–39 mm section	1 200	1 170	1 100	1 100
Over 40 mm section	1 150	1 120	1 050	1 050

Table 26.31 MISCELLANEOUS COPPER-BASE ALLOYS—*continued*

Alloy	*Aluminium bronze*	*Aluminium bronze*	*Copper manganese aluminium*	*Copper manganese aluminium*
Specification BS 1400: 1985	AB1	AB2	CMA1	CMA2
*Alloys grouping**	B	B	B	B
Mechanical properties—SI units (Imperial units in brackets) in order sand cast, chill cast, centrifugally cast				
Typical tensile stress				
MPa	500–590, 540–620, 560–650	640–700, 650–740, 670–730	650–730, 670–740, —	740–820, —, —
(tonf in^{-2})	(32.4–38.2, 35.0–40.1,36.3–42.1)	(41.4–45.3, 42.1–47.9, 43.4–47.3)	(42.1–47.3, 43.4–47.9, —)	(47.9–53.1, —, —)
Typical 0.2% proof stress				
MPa	170–200, 200–270, 200–270	250–300, 250–310, 250–310	280–340, 310–370, —	380–470, —, —
(tonf in^{-2})	(11.0–13.0, 13.0–17.5, 13.0–17.5)	(16.2–19.4, 16.2–20.1, 16.2–20.1)	(18.1–22.0, 20.1–24.0, —)	(24.6–30.4, —, —)
Typical elongation $5.65\sqrt{S_0}$%	18–40, 18–40, 20–30	13–20, 13–20, 13–20	18–35, 27–40, —	9–20, —, —
Typical hardness range HB	90–140, 130–160, 120–160	140–180, 160–190, 140–180	160–210, —, —	220–260, —, —

Alloy	*Nickel silver*	*High-conductivity copper*	*Copper chromium*	*High-strength cupro-nickel*
Specification BS 1400: 1985	—	HCC1**	CC1–WP††	—
*Alloy grouping**	—	B	B	B
Composition % (Single figures indicate maximum)				
Aluminium	—	—	—	—
Iron	1.0	—	—	1.0–1.4
Nickel	18–22	—	—	28.0–32.0
Manganese	1.0	—	—	1.0–1.4
Zinc	6.0–10.0	—	—	—
Silicon	0.15	—	—	0.35–0.50§§
Tin	2.5–4.0	—	—	—
Lead	4.0–6.0	—	—	0.01
Phosphorus	0.05	—	—	0.02
Magnesium	—	—	—	—
Chromium	—	—	0.6–1.2	0.3
Copper	REM	B.S. 1035–1037 grade	REM	REM
Total impurities	1.0 (incl. Fe)	—	—	—¶¶

Properties of material				
Suitability for:				
Sand casting	2	2	2	2
Chill casting	—	5	5	2
Gravity die casting	—	3	3	—
Centrifugal	—	2	2	—
Continuous	—	3	3	—
Pressure tight castings (sand)				
Thin sections	—	1	2	1
Thick sections	—	2	2	2
Machining	2	3	3	2
Corrosion resistance	Natural and sea-water applications	Very good	Very good	Excellent
Fluidity	Fair	Good	Fair	Fair
Strength at elevated temperatures	—	Oxidize more readily than the other alloys specified in BS 1400		Good up to 300 °C
Electrical conductivity % IACS at 15 °C	5	90	80	5
Density ($g\,cm^{-3}$)	8.7	8.9	8.85	—
Casting temperature range, °C				
Under 13 mm section	1 300	1 200	1 230	1 450
13–39 mm section	1 280	1 170	1 190	1 425
Over 40 mm section	1 250	1 130	1 150	1 400
Mechanical properties—SI units (Imperial units in brackets) in order sand cast, chill cast, centrifugally cast				
	Sand cast			Sand cast
Typical tensile stress				
MPa	309	160–190, —, —	270–340, —, —	540–618
($tonf\,in^{-2}$)	(20.0)	(10.4–12.3, —, —)	(17.5–22.0, —, —)	(35–40)
Typical 0.2% proof stress	(0.5%)			(0.5%)
MPa	185	—	170–250, —, —	355–386
($tonf\,in^{-2}$)	(12.0)	—	(11.0–16.2, —, —)	(23–25)
Typical elongation $5.65\sqrt{S_0}$%	($4\sqrt{S_0}$)			($4\sqrt{S_0}$)
	15.0	23–40, —, —	18–30, —, —	20–25
Typical hardness range HB	80–110	—	Mandatory 100 min	160 (typical)

* *See* footnote † to Table 26.27.
† When castings to be welded lead not to exceed 0.01%
‡ *See* footnote § to Table 26.27.
§ *See* footnote ** to Table 26.27.
¶ *See* footnote §§ to Table 26.27.
** Maximum resistivity 0.019 $\mu\Omega\,m^{-1}$.
†† Maximum resistivity 0.022 $\mu\Omega\,m^{-1}$.
§§ Can be reduced to 0.2% to improve weldability under severe constraint.
¶¶ Others C 0.04% S 0.02%
Cr 0.30% Nb 1.20–1.40%

Table 26.32 TYPICAL COMPOSITIONS OF NICKEL CASTING ALLOYS

Alloy name	*Chemical composition—wt% nominal or range—(not specification) bal. nickel*													
	C	Si	Mn	Cu	Cr	Fe	Mo	Co	Ti	Al	W	Nb	*Others*	*Spec.*
Nickel	0.1/0.3	1/2	1/1.5	0.3	—	1	—	—	—	—	—	—	Mg 0.08/0.2, S 0.05 max Pb 0.005 max	ASTM 494 M3F2
Monel† Low Si	0.1/0.3	0.5/1.5	0.5/1.5	28/32	—	3	—	—	—	—	—	—	Mg 0.08/0.12, S 0.05, Pb 0.005 max	494M3F2
Monel Med Si	0.15	2.5/3	0.5/1.5	28/32	—	3	—	—	—	—	—	—	Mg 0.08/0.12, S 0.05 max Pb 0.005 max	BS 3071 NA2
Monel High Si	0.15	3.5/4.5	0.5/1.5	28/32	—	3	—	—	—	—	—	—	Mg 0.08/0.12, S 0.05 max, Pb 0.005 max	BS 3071 NA3
Nichrome†	0.8	1.5/2.0	0.5/1.5	—	15/19	9/16	—	—	—	—	—	—	—	—
Hastelloy†	0.12	1	1	—	1	4/6	26/30	2.5	—	—	—	—	V 0.2/0.6, S 0.05 max, Pb 0.005 max	AMS 5396*
Hastcalloy† C	0.12	1	1	—	15.5/17.5	4.5/7	16/18	2.5	—	—	3.75/5.23	—	S 0.05 max, Pb 0.005 max	AMS 5388C/9A
Hastealloy† D	0.12	8.5/10	0.5/1.25	2/4	1	2	—	1.5	—	—	—	—	—	—
Hastcalloy† X	0.05/0.15	1	1	—	20/23	17/20	8/10	0.5/2.5	—	—	0.2/1	—	—	AMS 5390
Nimocast† 80	0.07	0.4	0.4	—	19.5	2	—	—	2.5	1.5	—	—	Ca 0.02 max, Pb 0.005 max	—
Nimocast† 90	0.07	0.4	0.4	—	19.5	2	—	17	2.5	1.5	—	—	Ca 0.2 max, Pb 0.005 max	—
Nimocast† 242	0.35	0.4	0.5	0.2	22	0.75	10.5	10	0.3	0.2	—	—	Pb 0.005 max	—
Nimocast† PE10	0.05	0.25	0.3	0.2	20	3	6	—	—	—	2.5	7	—	AFNOR NC 20NH
Nimocast† PD16	0.13	0.5	0.5	0.5	6	0.5	2	—	0.5	6	11	1.5	—	—
Nimocast† 263	0.06	0.4	0.6	0.2	20	0.7	6	20	2	0.5	—	—	—	—
IN-100	0.18	0.2	0.2	0.2	9.5/10.5	0.5	2.75/3.5	15	5	5.5	—	—	V 1.0	AFNOR-NK 15 CAT
IN-162	0.1/0.15	0.3	0.2	—	9/11	0.5	3.5/4.5	—	0.6/1.2	6.2/6.7	2	3	—	—
IN-591	0.1	—	—	—	3	—	—	12	—	5.75	19	—	Ta 3, Zr 0.37, B 0.03	—
IN-643	0.4/0.55	1	—	—	24/26	5	0.3/0.8	11/13	0.01/0.25	—	9	2	—	—
IN-657	0.1	—	—	—	48/52	1	—	—	—	0.1	—	1.5	—	—
IN-738LC	0.11	—	—	—	16	—	1.7	8.5	3.4	3.4	2.6	0.9	Ta 1.7, Zr 0.05, B 0.01	—
IN-792	0.12	—	—	—	12.4	—	1.9	9	4.5	3.1	3.8	—	Ta 3.9, Zr 0.1, B 0.02	—
IN-939	0.15	—	—	—	22.5	—	—	19	1.9	3.7	2	1	Ta 1.4, Zr 0.1, B 0.01	—
IN-940	0.04	—	—	—	50	—	2.5	—	2	1	—	—	Zr 0.3, B 0.003	—

IN-6201	0.03	—	—	—	20	—	0.5	20	3.6	2.5	2.3	1	Ta 1.5, Zr 0.05, B 0.8	—
IN-6212	0.15	—	—	—	12	—	3	6	4.7	4.5	2	—	Zr 0.03, B 0.02	—
IN-6203	0.15	—	—	—	22			19	3.5	2.3	2	0.8	Ta 1.1, Hf 0.75, Zr 0.1, B 0.01	—
C242	0.34	—	—	—	20.5	—	10.5	10	0.3	0.2	—	—		
C263	0.06	—	—	—	20	—	5.8	20	2.2	0.5	—	—	Zr 0.04, B 0.008	
713C	0.12	—	—	—	12.5	—	4.2	—	0.8	6.1	—	2.2	Zr 0.1, B 0.012	
713LC	0.05	—	—	—	12	—	4.5	—	0.6	5.9	—	2	Zr 0.1, B 0.010	
B1990	0.1	—	—	—	8	—	6	10	1	6	—	—	Ta 4, Zr 0.1, B 0.015	
MAR-M002†	0.15	—	—	—	9	—	—	10	1.5	5.75	10	1	Zr 0.06, B 0.013, Hf 1.6	
MAR-M200†	0.15	—	—	—	9	—	—	10	2	5	12	1	Zr 0.05, B 0.015	
MAR-M200+Hf†	0.14	—	—	—	9	—	—	10	2	5	12	1	Hf 1.8, Zr 0.08, B 0.02	
MAR-M246†	0.15	—	—	—	9	—	2.5	10	1.5	5.5	10	—	Ta 1.5, Zr 0.05, B 0.015	
MAR-M247†	0.15	—	—	—	8.3	—	0.7	10	1	5.5	10	—	Ta 3, Nf 1.5, Zr 0.05, B 0.015	
MAR-M421†	0.15	—	—	—	15.8	—	2	9.5	1.8	4.3	3.8	2	Zr 0.05, B 0.015	
MAR-M432†	0.15	—	—	—	15.5	—	—	20	4.3	2.8	3	2	Ta 2, Zr 0.05, B 0.015	
M-21	0.13	—	—	—	5.7	—	2	—	—	6	11	1.5	Zr 0.12, B 0.02	
M-22	0.13	—	—	—	5.7	—	2	—	—	6.3	11	—	Ta 3, Zr 0.6	
Rene 77†	0.07	—	—	—	146	—	4.2	15	4.3	4.3	—	—	Zr 0.04, B 0.016	
Rene 80†	0.17	—	—	—	14	—	4	9.5	5	3	4	—	Zr 0.03, B 0.015	
UDIMET 500†	0.07	—	—	—	18	—	4.2	19	3	3	—	—	Zr 0.05, B 0.007	
UDIMET 710†	0.07	—	—	—	18	—	3	15	5	2.5	1.5	—	Zr 0.05, B 0.020	
CMSX 2/3†	—	—	—	—	8	—	0.6	4.6	1	5.6	8	—	Ta 6, Hf 0.1	
CMSX 4†	—	—	—	—	6	—	0.6	10	1	5.6	6	—	Ta 6, Hf 0.1, Re 3	
CMSX 6†	—	—	—	—	9.8	—	3	5	4.7	4.8	—	—	Ta 2, Hf 0.1	
SRR 99	—	—	—	—	8.5	—	—	5	2.2	5.5	9.5	—	Ta 2.8	
A54	—	—	—	—	10	—	—	5	1.5	5	4	—	Ta 12	
SC 16	—	—	—	—	16	—	3	—	3.5	3.5	—	—	Ta 3.5	
INCONEL 625†*	0.2	—	—	—	21.6	—	8.7	—	0.2	0.2		3.9	—	
INCONEL 718†*	0.05	—	—	—	19	—	3	—	0.8	0.6	—	5.2	B 0.006	
INCOLOY 825†*	0.05	0.75	1.0	—	20/23	5	8/10	—	—	—	—	312/45	—	

† Registered trade mark.

* Strictly wrought but now commonly cast.

26.5 Nickel-base casting alloys

Table 26.33a PHYSICAL PROPERTIES AND USE OF NICKEL CASTING ALLOYS

Alloy name	*Casting characteristics*	*Melting range* °C	*Density* kg dm^{-3}	*Uses*
Nickel	C 0.2/0.3 for better castability	1 360–1 430	8.4	Corrosion resistant to alkalies
Ferry Metal (60% Cu)	Castability improves as Si increases	1 315–1 350	8.6	Good corrosion resistance
Monel Med Si	Tends to be hot short	1 290–1 320	8.6	Good corrosion and galling resistance
Monel High S	Tends to be hot short	1 260–1 290	8.5	Corrosion resistant with max hardness and galling resistance
Nichrome†	Susceptible to H absorption	1 375–1 425	8.2	Heat and oxidation resistance. Furnace windings
Hastelloy B†	Less liable to H absorption than Nichrome	1 320–1 350	9.2	Good corrosion resistance especially to HCl
Hastealloy C†	Castability—moderate	1 270–1 310	8.9	Good corrosion resistance over wide range
Hastealloy D†	Similar to Monels	1 110–1 120	7.8	Resistant to hot conc. H_2SO_4
Hastealloy X†	Moderate	1 380–1 400	8.2	High temp. service, gas turbines
Nimocast 80†	—	1 310–1 380	8.17	High temp. service gas turbines, furnace equipment
Nimocast 90†	Moderate	1 310–1 320	8.18	High temp. service gas turbines, furnace equipment
Nimocast 242†	—	1 370–1 400	8.4	High temp. thermal starch resistance
Nimocast PE10†	Good fluidity	1 235–1 340	8.84	Gas turbines, diesel engines
Nimocast 263†	—	1 268–1 385	7.75	Gas turbine blades
IN-100	Vacuum cast	1 265–1 335	7.75	Gas turbine blades
IN-162	Vacuum cast	1 275–1 300	8.1	Gas turbine blades
IN-591	Vacuum cast		9.13	Nozzle guide vanes
IN-643	Moderate	1 450–1 500	8.7	Reformer tubes
IN-657	Moderate	1 304–1 314	7.96	Reformer tubes and general high temp. service
IN-738LC	Vacuum cast	1 230–1 315	8.11	Industrial and marine texture and nozzle gjide vanes
IN-792	Vacuum cast	—	8.25	Industrial and marine turbine and nozzle guide vanes
IN-939	Vacuum cast	1 235–1 315	8.16	Turbine blades and nozzle guide vanes—gen. service
IN-6201	Vacuum cast	1 185–1 290	—	Turbine blades and nozzle guide vanes—gen. service
IN-6203	Vacuum cast	—	—	Turbine blades and nozzle guide vanes—gen. service
IN-6203	Vacuum cast	—	—	Turbine blades and nozzle guide vanes—gen. service

IN-6312	Vacuum cast	1 320–1 410		Turbine blades and nozzle guide vanes—gen. service
C242	Vacuum cast	1 225–1 340	8.4	Turbine blades and nozzle guide vanes—gen. service
C263	Vacuum cast	1 300–1 355	8.36	Turbine blades and nozzle guide vanes—gen. service
713C	Vacuum cast	1 260–1 290	7.91	Turbine blades and nozzle guide vanes—gen. service Turbo chargers
713LC	Vacuum cast	1 290–1 320	8.0	Turbine blades and nozzle guide vanes—gen. service Turbo chargers
B-1900	Vacuum cast	1 275–1 300	8.22	Servo gas turbine rotor blades
MAR-M002†	Vacuum cast	—	8.53	Aero gas turbine rotor and nozzle guide vanes
MAR-M002+Hf	Vacuum cast	—	8.53	Aero gas turbine rotor blades
MAR-M246†	Vacuum cast	1 315–1 345	8.44	Aero gas turbine rotor blades
MAR-M247†	Vacuum cast	—	8.53	Aero gas turbine rotor blades
MAR-M421†	Vacuum cast	—	8.03	Industrial and marine gas turbine blades + nozzle guide vanes
MAR-M432†	Vacuum cast	—	8.16	Industrial and marine gas turbine blades + nozzle guide vanes
M-21	Vacuum cast	1 320–1 375	8.53	Aero gas turbine nozzle guide vanes
M-22	Vacuum cast	1 280–1 375	8.63	Aero gas turbine nozzle guide vanes
Rene 77†	Vacuum cast	—	7.92	Industrial and marine turbine blades and nozzle guide vanes
Rene 80†	Vacuum cast	—	8.16	Industrial and marine turbine blades and nozzle guide vanes
UDIMET 500†	Vacuum cast	1 300–1 395	8.02	Industrial and marine turbine blades and nozzle guide vanes
UDIMET 710†	Vacuum cast	—	8.08	Industrial and marine gas turbine rotor blades
CMSX 2/3†	Vacuum cast	—	8.56	Aero gas turbine rotor blades
CMSX 4†	Vacuum cast	—	8.70	Aero gas turbine rotor blades
CMSX 6†	Vacuum cast	—	7.98	Aero gas turbine rotor blades
SRR 99	Vacuum cast	—	8.3	Aero gas turbine rotor blades
454	Vacuum cast	—	8.7	Aero gas turbine rotor blades
SC 16	Vacuum cast	—	8.2	Industrial and marine gas turbine blades and nozzle guide vanes
INCONEL 625†*	Vacuum cast	—	8.44	General high temperature service
INCONEL 718†*	Vacuum cast	1 205–1 345	8.22	General high temperature service
INCONEL 825†*	Similar to stainless steel	1 370–1 400	8.1	For agressive mineral acids, sour systems and stress corrosion cracking environments

† Registered trade mark.

* Strictly wrought but now commonly cast.

Table 26.33b MECHANICAL PROPERTIES OF NICKEL CASTING ALLOYS

Alloy name	*Heat treatment*	*Tensile stress* MPa (tonf in^{-2})	0.1% *proof stress* MPa (tonf in^{-2})	*Elongation* %	*Creep-rupture* MPa			
					100 h life		1 000 h life	
					870°C	980°C	870°C	980°C
Nickel	None	390 (25)	125 (8)	20	—	—	—	—
Ferry Metal	None	495 (32)	155 (10)	25	—	—	—	—
Monel Med Si	can be precipitation-treated	590 (38)	230 (15)	12	—	—	—	—
Monel High Si	to increase hardness	695 (45)	—	Nil	—	—	—	—
Nichrome†	None	465 (30)	185 (12)	10	—	—	—	—
Hastelloy B†	Sand castings—air cool from 1 120°C	540 (35)	390 (25)	8	—	—	—	—
Hastelloy C†	Sand castings—air cool from 1 200°C	540 (35)	310 (20)	8	—	—	—	—
Hastelloy D†	Furnace cool from 1 050°C—handle with care	770 (50)	—	1	—	—	—	—
Hastelloy X†	Sand castings—air cool from 1 200°C	480 (31)	320 (21)	12	—	—	—	—
Nimocast 80†	4 h/1 080°C + 16 h/700°C	770 (50)	525 (34)	14	—	—	—	—
Nimocast 90†	4 h/1 080°C + 16 h/700°C	730 (47)	525 (34)	12	125	—	83	—
Nimocast 242†	None	480 (31)	260 (17)	7	—	—	—	—
Nimocast PE10†	4 h/1 100°C + 16 h/750°C	710 (46)	560 (36)	10	144	—	107	—
Nimocast PD 16†	None	750(49)	680 (44)	3	—	—	—	—
Nimocast 263	None	1 000 (65)	650 (42)	—	—	—	—	—
IN-100	None	900 (58)	850 (55)	7	380	170	255	105
IN-162	None	930 (60)	770 (50)	6	—	—	—	—
IN-591	None	—	—	—	—	230	—	153
IN-643	None	600 (39)	280 (18)	12	—	(65)*	—	(50)*
IN-607	None	750 (49)	450 (29)	25	—	—	42	15
IN-738LC	2 h/1120°C + 24 h/845°C	—	—	—	315	130	215	83
IN-792	2 h/1120°C + 24 h/845°C	—	—	—	365	165	260	105
IN-939	4 h/1160°C + 6 h/1000°C + 24 h/900°C + 16 h/700°C	—	—	—	285	102	200	64
IN-940	—	—	—	—	(85)*	—	(55)*	—
IN-6201	4 h/1150°C + 16 h/900°C	—	—	—	(350)*	165	(240)*	95

IN-6212	2 h/1190°C + 24 h/845°C	—	—	—	380	160	250	100
IN-6203	8 h/1160°C + 16 h/700°C	—	—	—	315	—	(225)*	—
C242	None	—	—	—	90	45	59	—
C263	None	—	—	—	—	—	—	—
713C	None	—	—	—	290	145	195	90
713LC	None	—	—	—	295	140	205	90
B1900	None	—	—	—	385	170	255	105
MAR-M002†	—	—	—	—	415	185	285	125
MAR-M002+Hf†	19 h/1230°C + 32 h/870°C	—	—	—	450	200	—	140
MAR-M246†	50 h/845°C	—	—	—	440	195	290	125
MAR-M247†	16 h/870°C	—	—	—	450	185	290	125
MAR-M421†	2 h/1150°C + 4 h/1065°C + 16 h/780°C	—	—	—	310	125	215	83
MAR-M432†	4 h/1090°C + 16 h/760°C	—	—	—	295	140	215	87
M-21	None	—	—	—	380	188	(255)*	117
M-22	None	—	—	—	395	200	382	130
Rene 77†	4 h/1165°C + 4 h/1080°C + 24 h/925°C + 16 h/760°C	—	—	—	310	130	215	62
Rene 80†	2 h/1220°C + 4 h/1095°C + 4 h/1050°C + 16 h/845°C	—	—	—	350	165	240	105
UDIMET 500†	4 h/1150°C + 4 h/1080°C	—	—	—	230	90	165	—
UDIMET 710†	2 h/1150°C + 4 h/1065°C + 7 h/760°C	—	—	—	305	150	215	76
CMSX 2/3†	3 h/1302°C + 5 h/980°C + 20 h/870°C	—	—	—	480	240	350	170
CMSX 4†	—	—	—	—	580	275	435	190
CMSX 6†	3 h/1238°C + 3 h/1271°C + 3 h/1277°C + 20 h/870°C	—	—	—	—	—	—	—
SRR 99	—	—	—	—	480	240	350	170
454	4 h/1288°C + 4 h/1080°C + 32 h/870°C	—	—	—	455	200	315	125
SC 16	3 h/1250°C + 4 h/1100°C + 24 h/850°C	—	—	—	(376)*	—	(276)*	—
INCONEL 625†*	None	—	—	—	97	34	76	28
INCONEL 718†*	1 h/1095°C + 1 h/955°C + 8 h/720°C CF + 8 h/620°C	545 (35)	0.2% 290/400 (19/26)	20	—	—	—	—
INCOLOY 825†*	None	296/320 (19/21)	0.2% 170/200 (11/13)	20/25	—	—	—	—

† Registered trade mark.

* Wrought but not commonly cast.

()* Extrapolated.

26.6 Magnesium alloys

Table 26.34 ZIRCONIUM-FREE MAGNESIUM ALLOYS

Grain refined (0.05–0.2 mm chill cast) when superheated to 850–900°C or suitably treated with carbon (as hexachlorethane)

Elektron designation	A8		A8 (*High purity*)	
ASTM designation	AZ81		AZ81	
Specifications BS 2970: 1989	MAG1M*(GP)†	MAG1TB*(GP)	MAG2M(SP)†	MAG2TB(SP)
BSS L series	—	3L. 112	—	—
Equivalent DTD	—	—	684A	690A
Composition % (Single figures indicate maximum)				
Aluminium	7.5–9.0		7.5–9.0	
Zinc	0.3–1.0		0.3–1.0	
Manganese	0.15–0.4		0.15–0.7	
Copper	0.15		0.005	
Silicon	0.3		0.01	
Iron	0.05		0.003	
Nickel	0.01		0.001	
Cu + Si + Fe + Ni	0.40		—	
Materialaproperties				
Founding	Good		Good	
Characteristics	Sand and permanent‡ mould		Special melting technique required	
Tendency to hot tearing	Little		Little	
Tendency to micro-porosity	Appreciable		Appreciable	
Castability§	A		A	
Weldability (Ar-Arc process)	Good		Good	
Relative damping capacity¶	C		C	
Strength at elevated temperature**	C		C	
Corrosion resistance	Moderate		Modcrate	
Density, g cm^{-3}	1.81		1.81	
Liquids, °C	600		600	
Solidus, °C	475		475	
Non-equilibrium solidus, °C	420		420	
Casting temperature range, °C	680–800		680–800	
Heat treatment				
Solution:				
Time, h	—	12 (min)	—	12 (min)
Temperature, °C	—	435 (max)‡‡	—	435 (max)‡‡
Cooling	—	Air, oil or water	—	Air, oil or water

Elektron designation	AZ91			*C alloy*		
ASTM designation	AZ91					
Specifications BS 2970: 1989	MAG3M(GP)	MAG3TB(GP)	MAG3TF(GP)	MAG7M(GP)	MAG7TF(GP)	
BSS L series	—	3L.124	3L.125	—	—	—
Equivalent DTD	—	—	—	—	—	—
Composition % (Single figures indicate maximum)						
Aluminium		9.0–10.5			7.5–9.5	
Zinc		0.3–1.0			0.3–1.5	
Manganese		0.15–0.4			0.15–0.8	
Copper		0.15			0.35	
Silicon		0.3			0.40	
Iron		0.05			0.05	
Nickel		0.01			0.02	
Cu+Si+Fe+Ni		0.40			0.75	
Material properties						
Founding		Good			Good	
Characteristics		Sand, permanent mould and die (pressure)			Sand, permanent mould and die (pressure)	
Tencency to hot tearing		Little			Little	
Tendency to micro-porosity		Less than MAG1			Less than MAG1	
Castability§		A			A	
Weldability (Ar-Arc process)		Good, but some difficulty with die castings			Good, but some difficulty with die castings	
Relative damping capacity¶		C			C	
Strength at elevated temperature**		C			C	
Corrosion resistance		Moderate			Moderate	
Density, g cm^{-3}		1.83			1.82	
Liquidus, °C		595			600	
Solidus, °C		470			475	
Non-equilibrium solidus, °C		420			420	
Casting temperature range, °C		680–800			680–800	
Heat treatment						
Solution:						
Time, h	—		16 (min)	—		16 (min)
Temperature, °C	—		435 (max)‡‡	—		435 (max)‡‡
Cooling	—		Air, oil or water	—		Air, oil or water

Table 26.34 ZIRCONIUM-FREE MAGNESIUM ALLOYS—*continued*

Elektron designation *ASTM designation*	AZ91E	AZ91(HP)	AZ91D	ZC63 ZC63
Specifications BS 2970: 1989		MAG11(GP)		—
BSS L series		—		—
Equivalent DTD		—		—
Composition % (Single figures indicate maximum)				
Aluminium		8.5–9.5		—
Zinc		0.45–0.9		5.5–6.5
Manganese		0.15–0.40		0.25–0.75
Copper		0.015		2.4–3.0
Silicon		0.020		0.20
Iron		0.005		0.05
Nickel		0.0010		0.01
Cu+Si+Fe+Ni		—		—
Material properties				
Founding	Sand and permanent mould		High pressure die	Sand, permanent and high pressure die
Characteristics	Good		Good	Good
Tendency to hot tearing	Little		Little	Little
Tendency to micro-porosity	Less than MAG1		Little	Little
Castability§	A		A	B
Weldability (Ar-Arc process)	Good		Difficult	Good
Relative damping capacity¶	C		C	C
Strength at elevated temperature**	C		C	B
Corrosion resistance	Excellent		Excellent	Moderate
Density, g cm^{-3}	1.83		1.83	1.84
Liquidus, °C	595		595	635
Solidus, °C	470		470	465
Non-equilibrium solidus, °C	420		420	—
Casting temperature range, °C	680–800		620–680	700–810
Heat treatment				
Time, h	16 (min)		Not suitable	8
Temperature, °C	435 (max)			440 (max)
Colling	Air, oil or water			oil or water

Elektron designation *ASTM designation*	A8 AZ81			A8 (*High purity*) AZ81
Specifications BS 2970: 1989	MAG1M*(GP)†	MAG1TB*(GP)	MAG2M(SP)†	MAG2TB(SP)
BSS L series	—	3L.122	—	—
Equivalent DTD	—	—	684A	690A
Heat treatment—continued				
Precipitation:				
Time, h	—	—	—	—
Temperature, °C	—	—	—	—
Stress relief:				
Time, h	2–4	—	2–4	—
Temperature, °C	250–330	—	250–330	—
Mechanical propefties—dand cast—(SI units first, Imperial units following in brackets)				
Tensile strength (min), MPa (tonf in^{-2})	140 (9.1)	200 (13.0)	140 (9.1)	200 (13.0)
0.2% proof stress (min), MPa (tonf in^{-2})	85 (5.5)	80 (5.2)	85 (5.5)	80 (5.2)
Elongation % (min) ($5.65\sqrt{S_0}$)	2	6	2	6
Mechanical properties—chill cast—(SI units first, Imperial units following in brackets)				
Tensile strength (min), MPa (tonf in^{-2})	185 (12.0)	230 (14.9)	185 (12.0)	230 (14.9)
0.2% proof stress (min), MPa (tonf in^{-2})	85 (5.5)	80 (5.2)	85 (5.5)	80 (5.2)
Elongation % (min) ($5.65\sqrt{S_0}$)	4	10	4	10
Applications	Automobile road wheels	Good ductility and shock resistance	High-purity alloy—offers good corrosion resistance	

Table 26.34 ZIRCONIUM-FREE MAGNESIUM ALLOYS—*continued*

Elektron designation *ASTM designation*	AZ91			*C alloy*		
Specifications BS 2970: 1989	MAG3M(GP)	MAG3TB(GP)	MAG3TF(GP)	MAG7M(GP)	MAG7TB(GP)	MAG7TF(GP)
BSS L series	—	3L.124	3L.125	—	—	—
Equivalent DTD	—	—	—	—	—	—
Heat treatment—continued						
Precipitation:						
Time, h	—	—	8 (min)	—	—	8 (min)
Temperature, °C	—	—	210 (max)	—	—	210 (max)
Stress relief:						
Time, h	2–4	—	—	2–4	—	—
Temperature, °C	250–330	—	—	250–330	—	—
Mechanical properties—sand cast—(SI units first, Imperial units following in brackets)						
Tensile strength (min), MPa (tonf in^{-2})††	125 (8.1)	200 (13.0)	200 (13.0)	125 (8.1)	185 (12.0)	185 (12.0)
0.2% proof stress (min), MPa (tonf in^{-2})	95 (6.2)	85 (5.5)	130 (8.4)	85 (5.5)	80 (5.2)	110 (7.1)
Elongation % (min) ($5.65\sqrt{S_0}$)	—	4	—	—	4	—
Mechanical properties—chill cast—(SI units first, Imperial units following in brackets)						
Tensile strength (min), MPa (tonf in^{-2})	170 (11.0)	215 (13.9)	215 (13.9)	170 (11.0)	215 (13.9)	215 (13.9)
0.2% proof stress (min), MPa (tonf in^{-2})	100 (6.5)	85 (5.5)	130 (8.4)	85 (5.5)	80 (5.2)	110 (7.1)
Elongation % (min) ($5.66\sqrt{S_0}$)	2	5	2	2	5	2
Applications	For pressure tight applications Increased proof stress after full heat treatment			Principal alloy for commercial usage		

Elektron designation *ASTM designation*	AZ91E	AZ91(HP) AZ91D	ZC63 ZC63
Specifications BS 2970: 1989	MAG11(GP)		—
BSS L series	—		—
Equivalent DTD	—		—
Heat treatment — continued			
Precipitation:			
Time, h	8 (min)	Not suitable	16 (min)
Temperature, °C	210 (max)		200 (max)
Stress relief:			
Time, h	—	—	—
Temperature, °C	—	—	—
Mechanical properties — sand cast — (SI units first, Imperial units following in brackets)			
Tensile strength (min), MPa (tonf in^{-2})	200	Typical high	210
0.2% proof stress (min), MPa (tonf in^{-2})	130	pressure die-cast	125
Elongation % (min) ($5.65\sqrt{S_0}$)	2	properties	3
Mechanical properties — chill cast — (SI units first, Imperial units following in brackets)			
Tensile strength (min), MPa (tonf in^{-2})	215	200	210
0.2% proof stress (min), MPa (tonf in^{-2})	130	150	125
Elongation % (min) ($5.65\sqrt{S_0}$)	2	1	3
Applications	High purity alloy—offers excellent corrosion resistance. Max. temp. 120°C		Better foundability than AZ91 with superior elevated temperature properties

* M—as cast.
TS—Stress relieved only
TE—Precipitation treated only.
TB—Solution treated only.
TF—Solution and precipitation treated.

† GP General purpose alloy.
SP Special purpose alloy.

‡ Permanent mould = gravity die casting.

§ Ability to fill mould easily A, B, C, indicate decreasing castability.

¶ Damping capacity ratings.
A = Outstanding; better than grey cast iron.
B = Equivalent to cast-iron.
C = Inferior to cast-iron but better Al-base cast alloys.

** A = Particularly recommended.
B = Suitable but not especially recommended.
C = Not recommended where strength at elev. temps is likely to be an important consideration.

†† 1 MPa = 1 N mm^{-2} = 0.064 75 tonf in^{-2}

‡‡ SO_2 or CO_2 atmosphere.

Table 26.36 MAGNESIUM–ZIRCONIUM ALLOYS
Inherently fine grained (0.015–0.035 *mm chill cast*)

Elektron designation *ASTM designation*	Z5Z ZK51	RZ5 ZE41	ZRE1 EZ33
Specifications BS 2970: 1989	MAG4TE*(GP)†	MAG5TE(SP)	MAG6TE(SP)
BSS L series	2L. 127	2L. 128	2L. 126
Equivalent DTD	—	—	—
Composition % (Single figures indicate maximum)			
Zinc	3.5–5.5	3.5–5.5	0.8–3.0
Silver	—	—	—
Rare earth metals	—	0.75–1.75	2.5–4.0
Thorium	—	—	—
Zirconium	0.4–1.0	0.4–1.0	0.4–1.0
Copper	0.03	0.03	0.03
Nickel	0.005	0.005	0.005
Iron	—	—	—
Silicon	—	—	—
Manganese	—	—	—
Material properties			
Founding characteristics	Good in sand and permanent moulds§	Good in sand and permanent moulds	Excellent in sand and permanent moulds
Tendency to hot tearing	Marked	Some	Little
Tendency to micro-porosity	Very appreciable	Virtually none	None
Castability¶	B	A	A
Weldability (Ar-Arc Process)	Not recommended	Moderate	Very good
Relative damping capacity**	B/C	B/C	B
Strength at elevated temperature††	C	B	A
Resistance to creep at elevated temperature	Poor	Moderate	Good up to 250°C
Corrosion resistance	Moderate	Moderate	Moderate
Density, g cm^{-3} (20°C)	1.81	1.84	1.80
Liquidus, °C	640	640	640
Solidus, °C	560	510	545
Casting temperature range, °C	720–810	720–810	720–810

Heat treatment			
Solution:			
Time, h	—	—	—
Temperature, °C	—	—	—
Cooling	—	—	—
Precipitation:			
Time, h	16	2 followed by 16	8
Temperature, °C	180	330 180	200
	Air cool	Air cool after each	Air cool
Post-weld stress relief:			
Time, h	2	Precipitation	10
	330	treatment affords	250 max
	ionto precede precipitation treatment	s/relief	Air cool
Mechanical properties—sand cast—SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	230 (14.9)	200 (13.0)	140 (9.1)
0.2% proof stress min, MPa (tonf in^{-2})	145 (9.4)	135 (8.7)	95 (6.2)
Elongation, % ($5.65\sqrt{S_0}$) min	5	3	3
Mechanical properties—chill cast—SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	245 (15.9)	215 (13.9)	155 (10.0)
0.2% proof stress min, MPa (tonf in^{-2})	145 (9.4)	135 (8.7)	110 (7.1)
Elongation, % ($5.65\sqrt{S_0}$) min	7	4	3
Applications	High strength plus good ductility. Not suitable for spidery complex shapes	For high-strength pressure-tight applications	High degree of pressure tightness at room and elevated temperatures

Table 26.35 MAGNESIUM–ZIRCONIUM ALLOYS. *Inherently fine grained—continued*

Elektron designation *ASTM designation*	ZT1‡‡‡ HZ32	TZ6◇‡‡‡ ZH62	ZE63 ZE63
Specifications BS 2970: 1989 *BSS L series*	MAG8TE(SP)	MAG9TE(SP)	—
Equivalent DTD	5005A	5015A	5045
Composition % (Single figures indicate maximum)			
Zinc	1.7–2.5	5.0–6.0	5.5–6.0
Silver	—	—	—
Rare earth metals	0.10	0.20	2.0–3.0
Thorium	2.5–4.0	1.5–2.3	—
Zirconium	0.4–1.0	0.4–1.0	0.4–1.0
Copper	0.03	0.03	0.03
Nickel	0.005	0.005	0.005
Iron	0.01	0.01	0.01
Silicon	0.01	0.01	0.01
Manganese	0.15	0.15	0.15
Material properties			
Founding characteristics	As per MAG7 but more sluggish	Similar to MAG5	Good
Tendency to hot tearing	Little	Very little	Negligible
Tendency to micro-porosity	None	Low	Virtually none
Castability¶	C	B	A
Weldability (Ar-Arc process)	Very good	Fair	Very good***
Relative damping capacity**	B	C	B/C
Strength at elevated temperature††	A	B	C
Resistance to creep at elevated temperature	Good up to 350°C	Fair	Poor
Corrosion resistance	Moderate	Moderate	Moderate
Density, g cm^{-3} (20°C)	1.85	1.87	1.87
Liquidus, °C	645	630	625
Solidus, °C	550	520	516
Casting temperature range, °C	720–810	720–810	720–810
Heat treatment			
Solution:			3o for 12 mm sctn.
Time, h	—	—	70 for 25 mm sctn.
Temperature, °C	—	—	480†††
Cooling	—	—	Air blast or water spray
Precipitation:			
Time, h	16	2 followed 16	48 or 72
Temperature, °C	315	330 by 180	138 127
	Air cool	Air cool after each	Air cool

Post weld stress relief:			
Time, h	2	Pptn. treatment affords stress	—
Temperature, °C	350	relief	—
	Air cool		
Mechanical properties—sand cast—SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	185 (12.0)	255 (16.5)	275 (17.8)
0.2% proof stress min, MPa (tonf in^{-2})	85 (5.5)	155 (10.0)	170 (11.0)
Elongation, % ($5.65\sqrt{S_0}$) min	5	5	5
Mechanical properties—chill cast—SI units (Imperial units in brackets)			
Tensile strength min, MPa (tonf in^{-2})	185 (12.0)	255 (16.5)	Sand
0.2% proof stress min, MPa	85 (5.5)	155 (10.0)	Cast
Elongation, %)$5.65\sqrt{S_0}$) min	5	5	Alloy
Applications	Creep resistant alloy	For heavy duty structural usage	High strength with good ductility and excellent fatigue resistance. Structural parts aircraft, etc.

Elektron designation *ASTM*	MSR-A	MSR-B	MSR QE22	MTZ‡‡‡ HK31	EQ21 EQ21	WE54 WE54	WE43 WE43
Specifications BS 2970: 1972	—	MAG12TF(SP)	—	—	MAG13TF(SP)	MAG14TF(SP)	—
BSS L series	—	—	—	—	—	—	—
Equivalent DTD	5025A	5035A	5055	—	—	—	—
Composition % (Single figures indicate maximum)							
Zinc	0.2	0.2	0.2	0.3	0.2	0.2	0.2
Silver	2.0–3.0	2.0–3.0	2.0–3.0	—	1.3–1.7	—	—
Rare earth metals	1.2–2.0‡	2.0–3.0‡	1.8–2.5‡	0.1	1.5–3.0‡	2.0–4.0¶¶¶	2.4–4.4¶¶¶
Thorium	—	—	—	2.5–4.0	—	—	—
Zirconium	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0	0.4–1.0
Copper	0.03	0.03	0.03	0.03	0.05–0.10	0.03	0.03
Nickel	0.005	0.005	0.005	0.005	0.005	0.005	0.005
Iron	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Silicon	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Manganese	0.15	0.15	0.15	0.15	0.15	0.15	0.15
Yttrium	—	—	—	—	—	4.75–5.5	3.7–4.3

Table 26.35 MAGNESIUM–ZIRCONIUM ALLOYS. INHERENTLY FINE GRAINED—*continued*

Elektron designation *ASTM designation*	MSR-A —	MSR-B —	MSR QE22	MTZ‡‡‡ MK31	EQ21 EQ21	WE54 WE54	WE43 WE43
Specifications BS 2970: 1989	—	MAG12TF (SP)	—	—	MAG13TF(SP)	MAG14TF(SP)	—
BSS L series	—	—	—	—	—	—	—
Equipment DTD	5025A	5035A	5055	—	—	—	—
Material properties							
Founding characteristics	Good	Good	Good	Less easy to found than MSR types	Good	Good	Good
Tendency to hot tearing	Little	Little	Little	Very little	Little	Very little	Very little
Tendency to micro-porosity	Slight	Slight	Slight	Negligible	Slight	Slight	Slight
Cqstability¶	B	B	B	C	B	B	B
Weldability (Ar-Arc process)	Very good	Very good	Very good	Very good	Very good	Very good	Very good
Relative damping capacity**	B/C	B/C	B/C	B/C	B/C	B/C	B/C
Strength at elevated temperature††	A	A	A	A	A	A	A
Resistance to creep at elevated temperature	Good up to 200°C	Good up to 200°C	Good up to 200°C	Good up to 350°C for short time applications	Good up to 200°C	Very good up to 250°C	Very good up to 250°C
Corrosion resistance	Moderate	Moderate	Moderate	Moderate	Moderate	Excellent	Excellent
Density, g cm^{-3} (20°C)	1.81	1.82	1.81	1.84	1.81	1.85	1.85
Liquidus, °C	640	640	640	645	640	640	640
Solidus, °C	550	550	550	590	545	550	550
Casting temperature range, °C	720–810	720–810	720–810	720–810	720–810	720–810	720–810
Heat treatment							
Solution:							
Time, h	8	8	8	2	8	8	8
Temperature, °C	525‡‡	525‡‡	525‡‡	565‡‡,¶¶	520‡‡	525‡‡	525‡‡
Cooling	Water or oil	Water or oil	Water or oil	Air cool	Water or oil	Air cool	Water or oil
Precipitation:							
Time, h	16	16	16	16	16	16	16
Temperature, °C	200	200	200	200	200	250	250
	Air cool	Air cool	Air cool	Air cool	Air cool	Air cool	Air cool

Post-weld stress relief:							
Time, h Temperature, °C	1 510 followed by above quench and age			Repeat above cycle	1 505 followed by above quench and age	1 510 followed by above aircool and age	1 510 followed by above quench and age
Mechanical properties—sand cast—SI units (Imperial units in brackets)							
Tensile strength min, MPa (tonf in^{-2})	240 (15.5)	240 (15.5)	240 (15.5)	200 (13.0)	240	250	250
0.2% proof stress min, MPa (tonf in^{-2})	170 (11.0)	185 (12.0)	175 (11.3)	93 (6.0)	170	175	165
Elongation, % ($5.65\sqrt{S_0}$) min	4	2	2	5	2	2	2
Mechanical properties—chill cast—SI units (Imperial units in brackets)							
Tensile strength min, MPa (tonf in^{-2})	240 (15.5)	240 (15.5)	240 (15.5)		240	250	250
0.2% proof stress min, MPa (tonf in^{-2})	170 (11.0)	185 (12.1)	175 (11.3)	Usually sand	170	175	165
Elongation, % ($5.65\sqrt{S_0}$) min	4	2	2	2	cast	2	2
Applications	High strength in thick and thin section castings. Good elevated temperature (up to 250°C) short time tensile and fatigue props.		Similar to MSRA-B	Superior short time tensile and creep resistance at temperatures around 300°C	Similar to MSR alloys but less but less	Excellent strength up to 300°C for short time applications. Excellent corrosion resistance	Excellent strength up to 250°C for long time applications. Excellent corrosion resistance

* *See* footnote to Table 26.34.
† *See* footnote to Table 26.34.
‡ Neodymium-rich rare rearths (others Ce-rich).
¶ *See* footnote to Table 26.34.
** *See* footnote to Table 26.34.
§ *See* footnote to Table 26.34.
†† *See* footnote to Table 26.34.
‡‡ SO_2 or CO_2 atmosphere.
¶¶ Castings to be loaded into furnace at operating temperature.
*** But only before hydriding treatment.
††† In hydrogen at atmospheric pressure.
‡‡‡ Thorium containing alloys are being replaced by alternative magnesium based alloys.
¶¶¶ Neodymium and heavy rare earths.

26.7 Zinc base casting alloys

Table 26.36 ZINC BASE ALLOYS—COMPOSITIONS

Alloy†	BS1004A	BS1004B	ZA8	ZA12	ZA27	No. 2 alloy
Composition % (Single figures indicate maximum unless otherwise stated)						
Aluminium	3.8–4.3	3.8–4.3	8.0–8.8	10.5–11.5	25–28	3.5–4.3
Copper	0.10	0.75–1.25	0.8–1.3	0.5–1.2	2.0–2.5	2.5–3.2
Magnesium	0.03–0.06	0.03–0.06	0.015–0.030	0.015–0.030	0.01–0.02	0.03–0.06
Iron	0.10	0.10	0.10	0.075	0.10	0.075
Nickel	0.020	0.020	—	—	—	—
Lead	0.005	0.005	0.005	0.005	0.005	—
Cadmium	0.005	0.005	0.004	0.004	0.004	Pb+Cd 0.009
Tin	0.002	0.002	0.003	0.003	0.003	0.002
Thallium	0.001	0.001	—	—	—	—
Indium	0.0005	0.0005	—	—	—	—
Titanium	—	—	—	—	—	—
Chromium	—	—	—	—	—	—
Zinc	Remainder	Remainder	Remainder	Remainder	Remainder	Remainder
Dimensional changes after casting (mm m^{-1})						
After 5 weeks	−0.32	−0.69	Shrinkage 0.03% after 100 days	Shrinkage 0.005% after 30 days ambient, and 0.03% after 1 000 days. At 95°C, shrinkage followed by growth, i.e. zero change after 1 000 days	Shrinkage 0.005% after 30 days ambient, and 0.015% after 1 000 days. At 95°C rapid shrinkage then growth to +0.1% after 1 000 days.	
After 6 months	−0.56	−1.03				
After 5 years	−0.73	−1.36				
After 8 years	−0.79	−1.41				
Dimensional changes after stabilizing heat treatment (mm m^{-1}) 16 h at 100°C±5°C—air cool)						
After 5 weeks	−0.20	−0.22				
After 3 months	−0.30	−0.26				
After 2 years	−0.30	−0.37				
Ageing	At RT all the alloys show little decrease in strength. Exposure to elevated temperature (100°C) may result in decreases of up to 30%					
Applications and uses	Extensive use where a large number of strong dimensionally accurate metal components required, e.g. components of cars, domestic appliances, business machines, record players, hydraulic and pneumatic valves, toy models		Used for pressure diecastings requiring creep resistance. Gravity castings requiring excellent fluidity or very high quality electroplating	General purpose sand and gravity casting alloy and a higher strength diecasting alloy. Good wear and bearing properties	Strongest of the alloys. Used in the sand, gravity or pressure diecast form for applications where its strength is required. Best wear and bearing properties (comparable to SAE660 bronze)	Pressure die, sand and gravity die cast. For applications where hardness is an advantage. Sheet metal forming dies, moulds for plastics‡, zip fastener sliders

† *Note:* ZA alloys specified in Draft for Development DD139 (all alloys currently under CEN revision).

Table 26.36a ZINC BASE CASTING ALLOYS—PROPERTIES

Alloy	BS1004 A	BS1004 B	ZA8			ZA12			ZA27		*No. 2 alloy*	
Condition	*Pressure die cast*	*Pressure die cast*	*Gravity cast*	*Pressure die cast*	*Sand cast*	*Gravity cast*	*Pressure die cast*	*Sand cast*	*Gravity cast*	*Pressure die cast*	*Sand cast*	*Pressure die cast*
Density g/cm^3	6.7	6.7	6.3	6.3	6.0	6.0	6.0	5.0	5.0	5.0	6.6	6.6
Melting range °C	382–387	379–388	375–404	375–404	377–432	377–432	377–432	375–484	375–484	375–484	390–379	390–379
Casting temp. °C	400–425	400–425	420–500	410–430	450–550	450–550	450–500	500–600	500–600	500–550	420–440	400–425
Coefficient of thermal expansion ($\mu m/m^{-1}/k^{-1}$)	27.4	27.4	23.2	23.2	24.1	24.1	24.1	26.0	26.0	26.0	27.8	27.8
Specific heat J/Kg/K	418	418	435	435	448	448	448	534	534	534	418	418
Thermal conductivity W m^{-1} k^{-1}	113	110	115	115	116	116	116	126	126	126	—	105
Electrical conductivity % IACS	26	26	27.7	27.7	28.3	28.3	28.3	29.7	29.7	29.7	25	25
Resistivity $\mu\Omega$ cm	6.4	6.5	6.2	6.2	6.1	6.1	6.1	5.8	5.8	5.8	6.8	—
Tensile strength MPa	283	324	240	375	300	330	400	440	320	425	252	350
Yield strength (0.2% offset) MPa	—	—	210	290	210	260	320	370	260	370	177	—
Young's modulus (GPa)	83	92	86	86	82	82	82	78	78	78	83	85
Elongation % in (2 in (50 mm)	15	9	1–2	6–10	1–2	1.5–2.5	4–7	3–6	8–11	2.0–3.5	3	7
Hardness Brinell 500-10-30	83	92	90	100	95	90	100	115	95	120	100	100
Impact strength (un-notched RT)	58	57	—	40	25	—	30	44	60	12	7	47
Castability	Very good	Very good	Very good	Very good	Good	Good	Good (cold	Good with proper feeding and chilling	Good	Good (cold	Good	Very good

* Mechanical properties determined at thicknesses typical of the process and the alloy; they are intended for general guidance and comparison. (Source: International Lead Zinc Research Organisation.)

26.8 Steel castings

26.8.1 Casting characteristics

Casting is usually carried out at 1500–1700 °C, or even higher, according to the type of steel and section of the casting. Highly refractory sands with high resistance to the molten metal stream are essential. Liquid shrinkage is high, so that generous risers are needed and the metal is hot short. Manganese steels, in particular, attack all furnace and ladle refractories, and only olivine sand has adequate resistance to constitute a satisfactory moulding material, tolerably resistant to burn-on.

26.8.2 Heat treatment

HOMOGENIZING

High-temperature treatment intended to reduce interdendritic segregation.

ANNEALING

Heating above the critical range (Ac_3) for about 1 h per 25 mm of maximum cross-section and furnace cooling to nearly room temperature. Removes brittleness associated with coarse as-cast grain size or Widmanstätten structure, gives most complete relief of internal stresses, gives minimum yield stress and tensile strength, good ductility but poor impact values. Best magnetic properties in low carbon steels.

Table 26.37 STEEL CASTINGS FOR GENERAL ENGINEERING

Grade *BS* 3100	*Description of steels*	*Composition (maxima unless stated)*							
		C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
A1		0.25	0.60	0.90[1]	0.060	0.25[2]	0.15[2]	0.40[2]	Cu 0.30[2]
A2	C General	0.35	0.60	1.00	0.060	—	—	—	—
A3		0.45	0.60	1.00	0.060	—	—	—	—
A4		0.18/0.25	0.60	1.20/1.60	0.050	—	—	—	—
A5	1½ Mn general	0.25/0.33	0.60	1.20/1.60	0.050	—	—	—	—
A6		0.25/0.33	0.60	1.20/1.60	0.050	—	—	—	—
AL1	C Low temp. use	0.20	0.60	1.10[5]	0.040	—	—	—	—
AM1	C-High mag.	0.15	0.60	0.50	0.050	0.25[2]	0.15[2]	0.40[2]	Cu 0.30[2]
AM2	permeability	0.25	0.60	0.50	0.050	0.25[2]	0.15[2]	0.40[2]	Cu 0.30[2]
AW1	C-Case hardening	0.10/0.18	0.60	0.60/1.00	0.050	0.25[2]	0.15[2]	0.40[2]	Cu 0.30[2]
AW2	Wear resistance	0.40/0.50	0.60	1.00	0.050	0.25[2]	0.15[2]	0.40[2]	Cu 0.30[2]
AW3	surface hardening	0.50/0.60	0.60	1.00	0.050	0.25[2]	0.15[2]	0.40[2]	Cu 0.30[2]
B1	C–Mo Elevated temperature	0.20	0.20/ 0.60	0.50/1.00	0.050	0.25[2]	0.45/0.65	0.40[2]	Cu 0.30[2]
B2		0.20	0.60	0.50/0.80	0.050	1.00/1.50	0.45/0.65	0.40[8]	Cu 0.30[8]
B3	Cr–Mo for	0.18	0.60	0.40/0.70	0.050	2.00/2.75	0.90/1.20	0.40[8]	Cu 0.30[8]
B4	elevated temps.	0.25	0.75	0.30/0.70	0.040	2.50/3.50	0.35/0.60	0.40[8]	Cu 0.30[8]
B5		0.20	0.75	0.40/0.70	0.040	4.00/6.00	0.45/0.65	0.40[8]	Cu 0.30[8]
B6		0.20	1.00	0.30/0.70	0.040	8.00/10.0	0.90/1.20	0.40[8]	Cu 0.30[8]
B7	Cr–Mo–V for elevated temps.	0.10/0.15	0.45	0.40/0.70	0.030	0.30/0.50	0.40/0.60	0.30[8]	Cu 0.30[8] Sn 0.058 V 0.22/ 0.30
BL1		0.20	0.60	1.00	0.040	—	0.45/0.65	—	—
BL2	Ferritic for low temperatures	0.12	0.60	0.80	0.030	—	—	3.00/4.00	—

SUB-CRITICAL ANNEALING

Heating to a temperature below the Ac_1, and cooling slowly. Used for stress relief after welding, etc., and for softening high alloy steel castings.

NORMALIZING

Similar to annealing except that cooling is in still air. Gives a smaller ferrite/pearlite grain size, higher yield stress, tensile strength and impact, but slightly lower elongation values than annealing. Medium and higher carbon steels which harden appreciably are usually tempered subsequently. Normalizing may be preceded by annealing, or a prior normalizing treatment at a higher temperature to break down the cast structure.

QUENCHING (OR HARDENING) AND TEMPERING

Heating above the critical range, but not so high as for annealing or normalizing, and rapidly cooling in water, oil or air blast followed by reheating to a temperature below the critical range until the desired properties are achieved followed by air cooling, furnace cooling (if stress relief is also required) or cooling in water (to minimize temper embrittlement). Gives highest physical properties; high tempering temperatures usually give lower strength but higher elongation and impact values. Normally preceded by annealing.

SURFACE HARDENING

Heating the surface layers by flame or induction to a temperature above the critical range and quenching by water jets following the heat source or by immersion.

Supply	*Tensile strength* R_m	*Lower yield stress or* $R_{p0.2}$	*El %* on 5.65	*Bend test*		*Impact Charpy*	*Hardness*	*Limiting section thickness*
condition	MPa	MPa	$\sqrt{S_0}$	*Bend angle*	*Bend radius*	*V J*	*HB*	mm
HT	430	230	22	120[4]	1.5t	25[4]	—	—
HT	490	260	18	90[4]	1.5t	20[4]	—	—
HT	540	295	14	—	—	18[3]	—	—
HT	540/690	320	16	—	—	30	152/207	—
HT	620/770	370	13	—	—	25	179/229	100
HT	690/850	495	13	—	—	25	201/255	63
–[6]	430	230	22	—	—	20 (–40°C)	—	—
A or N	340/430	185	22	120	1.5t	—	—	—
A or N	400/490	215	22	120	1.5t	—	—	—
C, A or N	460[7]	—	12	—	—	25	—	—
Z, N or N & T	620	325	12	—	—	—	—	—
A, N or N & T	690	370	8	—	—	—	—	—
N & T	460	260	18	120[4]	1.5t	20[4]	—	—
N & T	480	280	17	120[4]	1.5t	30[4]	140/212	—
N & T	540	325	17	120[4]	3t	25[4]	156/235	—
N & T or H & T	620	370	13	120[4]	3t	25[4]	170/255	—
N & T or H & T	620	420	13	90[4]	3t	25[4]	179/255	—
N & T or H & T	620	420	13	—	—	—	179/255	—
N & T	510	295	17	120	3t	—	—	—
–6	460	260	18	—	—	20 (–50°C)	—	—
–6	460	280	20	—	—	20 (–60°C)	—	—

Table 26.37 STEEL CASTINGS FOR GENERAL ENGINEERING—*continued*

Grade BS 3100	*Description of steels*	*Composition (maxima unless stated)*							
		C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
BT1	Alloy-higher	—	—	—	0.050	—	—	—	—
BT2	tensile strengths	—	—	—	0.040	—	—	—	—
BT3		—	—	—	0.030	—	—	—	—
BW1	Alloy-case hardening	0.12/0.18	0.60	0.30/0.60	0.040	0.60/1.10	0.15/0.25	3.00/3.75	Cu 0.30[8]
BW2	Cr abrasion resistant	0.45/0.55	0.75	0.50/1.00	0.060	0.80/1.20	—	—	—
BW3		0.45/0.55	0.75	0.50/1.00	0.060	0.80/1.20	—	—	—
BW4	Cr-abrasion	0.55/0.65	0.75	0.50/1.00	0.060	0.80/1.50	0.20/0.40	—	—
BW10	Austenitic–Mn	1.00/1.25[9]	1.00	11.0 min	P 0.070 S 0.060	—	—	—	—
410C21[16]	13 Cr	0.15	1.00	1.00	0.040	11.5/13.5	—	1.00	—
420C29[16]		0.20	1.00	1.00	0.040	11.5/13.5	—	1.00	—
425C11	13Cr 4Ni	0.10	1.00	1.00	0.040	11.5/13.5	0.60	3.40/4.20	—
302C25[16]		0.12	1.50	2.00	0.040	17.0/21.0	—	8.00 min	—
304C12[16]		0.03	1.50	2.00	0.040	17.0/21.0	—	8.00 min	—
304C15[16]	Austenitic Cr–Ni	0.08	1.50	2.00	0.040	17.0/21.0	—	8.00 min	—
347C17[13,16]		0.08	1.50	2.00	0.040	17.0/21.0	—	8.50 min	Nb8 × C/1.0[12]
315C16[16]		0.08	1.50	2.00	0.040	17.0/21.0	1.00/1.75	8.00 min	—
316C12[16]		0.03	1.50	2.00	0.040	17.0/21.0	2.00/3.00	10.0 min	—
316C16[16]	Austenitic Cr–Ni–No	0.08	1.50	2.00	0.040	17.0/21.0	2.00/3.00	10.0 min	—
316C71[16]		0.08	1.50	2.00	0.040	17.0/21.0	2.00/3.00	8.00 min	—
317C16[16]		0.08	1.50	2.00	0.040	17.0/21.0	3.00/4.00	10.0 min	
318C17[16]		0.08	1.50	2.00	0.040	17.0/21.0	2.00/3.00	10.0 min	Nb8 × C/1.0[12]
452C11	Cr—for high	1.00	2.00	1.00	0.060	25.0/30.0	1.50	4.00	—
452C12	temp. use	1.00/2.00	2.00	1.00	0.060	25.0/30.0	1.50	4.00	—
420C24		0.25	2.00	1.00	0.060	12.0/16.0	—	—	—
302C35		0.20/0.40	2.00	2.00	0.060	17.0/22.0	1.50	6.00/10.0	—
309C30		0.50	2.50	2.00	0.060	22.0/27.0	1.50	10.0/14.0	—
309C40	High alloy for	0.50	2.00	2.00	0.060	25.0/30.0	1.50	8.00/12.0	—
310C45	high temp. use	0.50	3.00	2.00	0.060	22.0/27.0	1.50	17.0/22.0	—
311C11		0.50	3.00	2.00	0.060	17.0/23.0	1.50	23.0/28.0	—
330C12		0.75	3.00	2.00	0.060	13.0/20.0	1.50	30.0/40.0	—
331C60		0.75	3.00	2.00	0.060	15.0/25.0	1.50	36.0/46.0	—
334C11		0.75	3.00	2.00	0.060	10.0/20.0	1.50	55.0/65.0	—
309C32	High alloy for	0.20/0.45	1.50	2.50	0.040	24.0/28.0	1.50	11.0/14.0	N 0.2
309C35	high temp. use	0.20/0.50	1.50	2.00	0.040	24.0/28.0	1.50	11.0/14.0	—
310C40		0.30/0.50	1.50	2.00	0.040	24.0/27.0	1.50	19.0/22.0	—
330C11		3.35/0.55	1.50	2.00	0.040	13.0/17.0	1.50	33.0/37.0	—
331C40		0.35/0.55	1.50	2.00	0.040	17.0/21.0	1.50	37.0/41.0	—

1 For each 0.01% carbon below the max an increase of 0.04% Mn is permitted up to a max of 1.10%.
2 Residual elements: total shall not exceed 0.80%.
3 Only mandatory if specified by the purchaser.
4 Either a bend test or an impact test may be specified.
5 Mn/C ratio shall be greater than 3:1.
6 The heat treatment to be applied shall be at the discretion of the manufacturer.
7 Properties in the blank carburised and heat treated condition.
8 Residual elements.
9 The maximum carbon content may be increased to 1.35% by agreement.
10 Not applicable to free machining steels.

Supply condition	*Tensile strength* R_m MPa	*Lower yield stress or* $R_{p0.2}$ MPa	*El % on* $\sqrt{S_0}$ 5.65	*Bend test* *Bend angle*	*Bend radius*	*Impact Charpy V* J	*Hardness* HB	*Limiting section thickness* mm
H & T	690/850	495	11	—	—	35	201/255	—
H & T	850/1000	585	8	—	—	25	248/302	—
H & T	1000/1160	695	6	—	—	20	293/341	—
A	1000[7]	—	7	—	—	20	—	—
A, N & T or	—	—	—	—	—	—	—	—
H & T	—	—	—	—	—	—	201/255	—
A, N & T or	—	—	—	—	—	—	—	—
H & T	—	—	—	—	—	—	293 min	—
A, N & T or	—	—	—	—	—	—	—	—
H & T	—	—	—	—	—	—	341 min	—
WQ	—	—	—	—	—	—	—	—
HT	540	370	15	120[10]	2t	—	152/207	—
HT	690	465	11	—	—	—	201/255	—
HT	770	620	12	—	—	30	235/321	—
ST	480	240[15]	26[11]	—	—	—	—	—
ST	430	215[15]	26[11]	—	—	41[3,10] (−196°C)	—	—
ST	480	240[15]	26[11]	—	—	41[3,10] (−196°C)	—	—
ST	480	240[15]	22[11]	—	—	20[3,10] (−196°C)	—	—
ST	480	240[15]	26[11]	—	—	34[3,10] (−196°C)	—	—
ST	430	215[15]	26[11]	—	—	41[3,10] (−196°C)	—	—
ST	480	240[15]	26[11]	—	—	34[3,10] (−196°C)	—	—
ST	510	260[15]	26[11]	—	—	34[3,10] (−196°C)	—	—
ST	480	240[15]	22[11]	—	—	—	—	—
ST	480[14]	240[15]	18[11]	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—[6]	—	—	—	—	—	—	—	—
—	560	—	3	—	—	—	—	—
—	510	—	7	—	—	—	—	—
—	450	—	7	—	—	—	—	—
—	450	—	3	—	—	—	—	—
—	450	—	3	—	—	—	—	—

11 For free machining grades the minimum elongation shall be 12%.

12 Gy agreement the Nb may be replaced by Ti in the range 5 × C/0.70%.

13 If required with specified low temperature impact properties the carbon content shall be 0.06% max and the niobium 0.90% max.

14 The minimum value for a free version shall be 460 N/mm².

15 1% PS value.

16 If a free machining grade is specified the sulphur content may be as high as 0.5% and/or other suitable elements may be present. Free machining grades shall be denoted by the letter F after the grade designation.

17 Properties minima unless stated.

18 HT—Heat treated, A—annealed, N—normalised. C—As cast, T—tempered, H & T—hardened and tempered, WA—water quenched, ST—solution treated.

Table 26.38a STEEL CASTINGS FOR PRESSURE PURPOSES

Designation BS	*Description of steels*	*Composition (maxima unless stated)*							
		C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
1504-161-430	Carbon steels	0.25	0.60	0.90[1]	0.050	0.25[3]	0.15[3]	0.40[3]	Cu 0.30[3]
1504-161-480		0.30	0.60	0.90[1]	0.050	0.25[3]	0.15[3]	0.40[3]	Cu 0.30[3]
1504-161-540	C–Mo	0.35	0.60	1.10[2]	0.050	0.25[3]	0.15[3]	0.40[3]	Cu 0.30[3]
1504-245		0.20	0.20/0.60	0.50/1.00	0.040	0.25[4]	0.45/0.65	0.40[4]	Cu 0.30[4]
1504-503LL60	3½ Ni	0.12	0.60	0.80	0.030	—	—	3.0/4.0	—
1504-621	1¼ Cr Mo	0.20	0.60	0.50/0.80	0.050	1.0/1.5	0.45/0.65	0.40[6]	Cu 0.30[6]
1504-622	2½ Cr Mo	0.18	0.60	0.40/0.70	0.050	2.0/2.75	0.90/1.2	0.40[6]	Cu 0.30[6]
1504-623	3 Cr Mo	0.25	0.75	0.30/0.70	0.040	2.5/3.5	0.35/0.60	0.40[6]	Cu 0.30[6]
1504-625	5 Cr Mo	0.20	0.75	0.40/0.70	0.040	4.0/6.0	0.45/0.65	0.40[6]	Cu 0.30[6]
1504-629	9 Cr Mo	0.20	1.00	0.30/0.70	0.040	8.0/10.0	0.90/1.20	0.40[6]	Cu 0.30[6]
1504-660	Cr Mo V	0.10/0.15	0.45	0.40/0.70	0.030	0.30/0.50	0.40/0.60	0.30[6]	Cu 0.30[6] Sn 0.05[6]
1504-420C29	13 Cr	0.20	1.0	1.0	0.040	11.5/13.5	—	1.0	Cu 0.30[6]
1504-425C11	13 Cr 4 Ni	0.10	1.0	1.0	0.040	11.5/13.5	0.60	3.4/4.2	—
1504-304C15	Austenitic Cr Ni	0.08	1.5	2.0	0.040	17.0/21.0	—	8.0 min	—
1504-304C12	Austenitic Cr Ni	0.03	1.5	2.0	0.040	17.0/21.0	—	8.0 min	—
1504-347C17	low C stabilized	0.08[11]	1.5	2.0	0.040	17.0/21.0	—	8.5 min	Nb8 × C/1.0[11,12]
1504-315C16	Austenitic Cr Ni 1½ Mo	0.08	1.5	2.0	0.040	17.0/21.0	1.0/1.75	8.0 min	—
1504-316C12		0.03	1.5	2.0	0.040	17.0/21.0	2.0/3.0	10.0 min	—
1504-316C16	Austenitic Cr Ni	0.08	1.5	2.0	0.040	17.0/21.0	2.0/3.0	10.0 min	—
1504-316C71	2½ Mo	0.08	1.5	2.0	0.040	17.0/21.0	2.0/3.0	8.0 min	—
1504-318C17		0.08	1.5	2.0	0.040	17.0/21.0	2.0/3.0	10 min	Nb8 × C/1.0[12]
1504-317C12	Austenitic Cr Ni	0.03	1.5	2.0	0.040	17.0/21.0	3.0/4.0	10.0 min	—
1504-317C16	3½ Mo	0.08	1.5	2.0	0.040	17.0/21.0	3.0/4.0	10.0 min	—
1504-364C11	Austenitic Cr Ni	0.07	2.5	2.0	0.030	20.0/24.0	3.0/6.0	20.0/26.0	Cu 2.0 Nb 0.50
1504-332C11	Mo Cu high alloy	0.07	1.5	2.0	0.040	19.0/22.0	2.0/3.0	26.5/30.5	Cu 3.0/4.0
1504-310C40	Austenitic Cr Ni High alloy	0.30/0.50	1.5	2.0	0.040	24.0/27.0	1.50[6]	19.0/22.0	—
1504-330C11	Austenitic Ni Cr High alloy	0.35/0.55	1.5	2.0	0.040	13.0/17.0	1.50[6]	33.0/37.0	—

Treatment	*Tensile strength* R_m MPa	*Lower yield stress or* $R_{p0.2}$ MPa	*EI A %* on $5.65\sqrt{S_0}$	*Bend test*		*Impact Charpy V*	*Hardness HB*
				Bend angle	*Bend radius*	*J*	
A or N	430	230	22	120	1.5t[5]	25 @ RT[5] 20 @ −40°C[8]	—
A or N	480	245	20	90	1.5t[5]	20 @ RT[5]	—
A or N	540	280	13	90	1.5t[5]	20 @ RT[5]	—
N & T or Q & T	460	260	18	120	1.5t[5]	20 @ RT[5] 20 @ −50°C[8]	—
N & T or H & T	460	280	20	—	—	20 @ −60°C	134/187
N & T	480	280	17	120	1.5t[5]	30 @ RT[5]	140/212
N & T	540	325	17	120	3t[5]	25 @ RT[5]	156/235
N & T or H & T	620	370	13[7]	120	3t[5]	25 @ RT[5]	179/255
H & T	620	420	13[7]	90	3t[5]	25 @ RT[5]	179/255
H & T	620	420	13[7]	—	—	—	179/255
N & T	510	295	17	120	3t[5]	—	—
V 0.22/0.30 Al[9]							
H & T	620	450	13[7]	120	3t[5]	25 @ RT[5]	179/235
H & T	770	620	12[7]	—	—	30 @ RT[5]	235/321
ST	480	240[10]	26	—	—	41 @ −196°C[8]	—
ST	430	215[10]	26	—	—	41 @ −196°C[8]	—
ST	480	240[10]	22	—	—	20 @ −196°C[8]	—
ST	480	240[10]	26	—	—	34 @ −196°C[8]	—
ST	430	215[10]	26	—	—	41 @ −196°C[8]	—
ST	480	240[10]	26	—	—	34 @ −196°C[8]	—
ST	510	260[10]	26	—	—	34 @ −196°C[8]	—
ST	480	240[10]	18	—	—	—	—
ST	430	215[10]	22	—	—	—	—
ST	480	240[10]	22	—	—	—	—
ST	430	200[10]	20	—	—	—	—
ST	430	200	20	—	—	—	—
—	450	—	7	—	—	—	—
—	450	—	3	—	—	—	—

Table 26.38b STEEL CASTINGS FOR PRESSURE PURPOSES—ELEMENTAL TEMPERATURE PROPERTIES—E DESIGNATION

Designation BS	*Description of steels*	*Minimum lower yield stress R_{el} or 0.2% proof stress, $R_{p0.2}$, MPa at a temperature in °C of*														
		20[13]	50[13]	100	150	200	250	300	350	400	450	500	550	600	650	700
1504-161-430E	Carbon steels	208	199	187	178	168	157	148	142	139	—	—	—	—	—	—
1504-161-480E		241	232	218	205	193	181	172	164	161	—	—	—	—	—	—
1504-245[14]	C–Mo	262	256	248	241	232	210	181	171	165	165	161	151	128	—	—
1504-622	2¼ Cr Mo	335	—	323	312	305	296	290	280	273	258	240	211	180	—	—
1504-625	5 Cr Mo	480	465	443	430	423	416	411	398	382	353	314	—	—	—	—
1504-316C16	Austenitic Cr Ni 1½ Mo	—	—	140	—	116	—	96	—	93	—	85	—	77	—	76
1504-316C71	Austenitic Cr Ni 2½ Mo	—	—	162	—	137	—	116	—	113	—	102	—	93	—	81

Notes for Table 26.38a and b

1 For each 0.01% carbon below the maximum an increase of 0.04% manganese will be permitted up to a maximum of 1.10%
2 For each 0.01% carbin below the maximum an increase of 0.05% manganese will be permitted up to a maximum of 1.60%
3 Ni+Cr+Mo+Cu=0.80% max
4 Ni+Cr+Cu=0.80% max
5 Either a bend test or an impact test may be specified but not both
6 Residual elements
7 This value may be increased to 15% min, subject to agreement at the time of enquiry and order
8 When specifically ordered
9 When used for deoxidation shall not exceed 0.25 kg/t
10 1% Proof stress
11 C content 0.06 max and Nb 0.9 max when low temperature properties are specified
12 Ti 5XC/0.70 may be substituted for Nb by agreement
13 Values at 20°C and 50°C are included for design purposes only and are not subjected to verification. All values except those at 50°C that are obtained by interpolation are based on tests according to BS 3688 and thus values at 20°C differ from the corresponding room temperature values given in this specification
14 Only apply to sections <32 mm
15 Properties minima unless stated
16 A—Annealed, N—normalised, T—tempered, Q & T—quenched and tempered, H & T—hardened and tempered, ST—solution treated

Table 26.39 WELDABLE CHROMIUM–NICKEL CENTRIFUGALLY CAST TUBES

BS	*Description*	*Grade*	*Composition (maxima unless stated)* C	Si	Mn	P	S	Cr	Mo	Ni	*Others*	*Treatment*	*Tensile strength* R_e MPa	*EI* % *on* 5.65 $\sqrt{S_0}$	*Maximum*[3] *wall thickness* mm
4534: 1969	18/11 Cr Ni 0.07C	1	0.04/0.09	1.00	2.00	0.030	0.030	17.0/19.0	0.50	11.0/13.5	—	C	450	26	20
	18/8 Cr Ni 0.07C	1F[1]	0.04/0.09	1.50	2.00	0.040	0.040	17.0/20.0	—	8.0 min	—	C	480	26	20
	18/21/1 Cr Ni Nb 0.07C	2	0.04/0.09	1.00	2.00	0.030	0.030	17.0/19.0	0.50	11.5/14.0	Nb 8 × C/1.0	C	450	22	20
	18/8/1 Cr Ni Nb 0.07C	2F[1]	0.04/0.09	1.50	2.00	0.040	0.040	17.0/20.0	—	8.0 min	Nb 8 × C/1.00	C	480	22	20
	17/3/2.5 Cr Ni Mo 0.07C	3	0.04/0.09	1.00	2.00	0.030	0.030	16.0/18.0	2.00/2.75	12.5/15.0	—	C	450	26	20
	18/8/3 Cr Ni Mo 0.07C	3F[1]	0.04/0.09	1.50	2.00	0.040	0.040	17.0/20.0	2.00/3.00	8.00 min	—	C	480	26	20
	20/10 Cr Ni 0.3C	4	0.25/0.35	0.50/1.50	2.00	0.030	0.040	18.0/21.0	0.50	9.00/11.5	-	C	480	22	20
	20/12 Cr Ni 0.3C	5	0.25/0.40	0.50/1.50	2.00	0.030	0.040	23.0/27.0	0.50	11.5/14.0	—	C Aged	510	9	20
	25/30 Cr Ni 0.4C	6	0.35/0.45	0.50/1.50	2.00	0.030	0.040	23.0/27.0	0.50	18.0/22.0	—	C	480	9	20
	25/20 Cr Ni 0.15C	7	0.15	0.50/1.50	2.00	0.030	0.040	23.0/27.0	0.50	19.0/23.0	—	C	450	22	20
	18/35 Cr Ni 0.45C	8	0.40/0.50[2]	0.50/1.50	2.00	0.030	0.040	17.0/21.0	0.50	33.0/37.0	—	C	450	7	20
	18/35 Cr Ni 0.5C	9	0.35/0.55	1.50/2.00	2.00	0.030	0.040	17.0/21.0	0.50	33.0/37.0	—	C	450	7	20
	18/35 Cr Ni 0.15C	10	0.15	0.50/1.50	2.00	0.030	0.040	17.0/21.0	0.50	33.0/37.0	—	C	420	22	20
	20/32 Cr Ni 0.1C	11	0.10	0.30/1.00	1.50	0.030	0.030	19.0/22.0	0.50	30.0/34.0	—	C	400	26	20

1 For use where ferrite content is to be within a specified range to facilitate welding.

2 By agreement this grade can be supplied to a C range of 0.35/0.45%.

3 Above 20 mm wall thickness properties shall be agreed between manufacturer and purchaser.

4 Properties minima unless stated.

5 C—As cast.

Table 26.40 AEROSPACE SERIES—STEEL CASTINGS—1973/1974

Designation BS	*Description of steels*	*Compositions (maxima unless stated)* %							
		C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
HC1	C 500 MPa	0.35	0.6	1.0	0.035	0.25[1]	0.15[1]	0.4[1]	Cu 0.3[1]
HC2	C Mn 550 MPa	0.25	0.6	1.7	0.035	0.25[1]	0.15[1]	0.4[1]	Cu 0.3[1]
HC3	1 Cr Mo Low alloy 700 MPa	0.3	0.6	0.8	0.35	1.2	0.4	—	Cu 0.3
HC4	3 Cr Mo 620/770 MPa	0.25	0.75	0.6	0.035	3.5	0.6	—	Cu 0.3
HC5	3 Ni Case hard. 700 MPa	0.18	0.6	0.6	0.035	0.25	0.15	3.5	Cu 0.3
HC6	3 Cr Mo Nitrid. 850/1000 MPa	0.3	0.75	0.6	0.020	3.5	0.7	0.4	Cu 0.3 V 0.02 Sn 0.03
HC7	3 Cr Mo 800/1080 MPa	0.32	0.75	0.8	0.025	3.5	0.7	0.4	Cu 0.4 V 0.02 Sn 0.03
HC8	3 Cr Mo 1150/1300 MPa	0.32	0.75	0.8	0.025	3.5	0.7	0.4	Cu 0.4 V 0.02 Sn 0.03
HC9	Ni Cr Mo 880/1080 MPa	0.34	0.6	0.8	0.025	1.3	0.7	3.0	Cu 0.4
HC10	Ni Cr Mo 1150/1300 MPa	0.34	0.6	0.8	0.025	1.3	0.7	3.0	Cu 0.4
HC101[2]	Pt. hard. Cr Ni Cu Mo 950 MPa	0.07	2.0	1.0	0.025	15.5	2.5	6.0	Cu 3.5 Nb 0.5
HC102[2]	Pt. hard. Cr Ni Cu Mo 1250 MPa	0.07	2.0	1.0	0.025	15.5	2.5	6.0	Cu 3.5 Nb 0.5
HC103	23 Cr Ni W corr. resist.	0.25	2.0	1.0	0.04	25.0	—	13.0	W 3.5
HC104	19 Cr 10 Ni, Vb corr. resist.	0.08	2.0	2.0	0.04	21.0	—	12.5	Nb 1.0
HC105	18 Cr 11 Ni 2.5 Mo Nb corr. resist.	0.08	1.5	2.0	0.04	20.0	3.0	12.5	Nb 1.0
HC106	Pt. hard. Cr Ni Cu corr. resist.	0.08	1.0	1.0	0.04	17.5	—	5.0	Cu 3.0 Ta+Nb 0.4
HC401	18 Ni Maraging Precision cast 1600/1850 MPa	0.03	0.1	0.1	0.01	0.25	4.9	17.5	Al 0.15 Co 11.0 Ti 0.6

Table 26.41a INVESTMENT CASTINGS—CARBON AND LOW ALLOY STEELS

Grade BS 3146 Part 1	*Description of steels*	*Composition (maxima unless stated)*							
		C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
CLA1-A		0.15/0.25	0.20/0.60	0.40/1.00	0.035	0.30[1]	0.10[1]	0.40[1]	Cu 0.30[1]
-B	C steels	0.25/0.35	0.20/0.60	0.40/1.00	0.035	0.30[1]	0.10[1]	0.40[1]	Cu 0.30[1]
-C		0.35/0.45	0.20/0.60	0.40/1.00	0.035	0.30[1]	0.10[1]	0.40[1]	Cu 0.30[1]
CLA2	$1\frac{1}{2}$ Mn	0.18/0.25	0.20/0.50	1.20/1.70	0.035	0.30[1]	0.10[1]	0.40[1]	Cu 0.30[1]
CLA3	Alloy steels 700–850 MPa	—	—	—	0.035	—	—	—	—
CLA4	Alloy steels 850–1000 MPa	—	—	—	0.035	—	—	—	—
CLA5-A	1000 MPa min	—	—	—	P 0.025)	—	—	—	—
-B		—	—	—	S 0.020)	—	—	—	—
CLA7	3 Cr Mo	0.15/0.25	0.30/0.80	0.30/0.60	0.035	2.50/3.50	0.35/0.60	0.40[4]	Cu 0.30[4]
CLA8	C Steels for surface hardening	0.37/0.45	0.20/0.60	0.50/0.80	0.035	0.30[1]	0.10[1]	0.40[1]	Cu 0.30[1]

Tensile strength R_m MPa	*Lower yield* $R_{p0.2}$ MPa	*EI A* %	*Z* %	*KI* ft/lb	*Hardness* HB	HV	HRB	HRC
500	215	15	—	25	—	—	—	—
550	310	13	—	30	—	—	-	—
700	480	12	—	30	201	200	—	—
620	480	14	—	25	179	175	88	—
700	350	13	—	30	197	200	93	—
850	600	8	—	15	248	255	—	22
880	700	8	30	30	262	265	—	27
1 150	940	5	14	10	331	335	—	35
880	700	8	30	30	262	625	—	27
1 150	940	5	14	10	331	335	—	35
950	800	12	30	15	—	—	—	—
1 250	950	8	15	8	375	400	—	40
—	—	—	—	—	—	—	—	—
460	200	20	•	—	—	—	—	—
500	210	20	••	—	—	—	—	—
1 250	1 030	8	20	—	375	395	—	40
1 600	1 500	6	25	10	461[3]	495[3]	—	49[3]

Notes:

1 Total residual elements shall not exceed 0.8%

2 A restricted range of oncomposition may be agreed if welding or brazing is intended. Castings in composition range are subject to Patent applications

3 Hardness values are for maraged castings

• Angle of bend 120°. Radius of bend 1.5t, t = teckiness of test piece

•• Angle of bend 120°. Radius of bend 2t, t = techiness of test piece

Treatment	*Tensile strength* R_m MPa	$R_{p0.2}$ MPa	*EI* % *on* $5.65\sqrt{S_o}$	*Impact Izod* ft. lbf	*Hardness* HB
N, N & T or H & T	430	195[3]	15	—	121/174[2]
N, N & T or H & T	500	215[3]	13	—	143/183[2]
N, N & T or H & T	540	245[3]	11	—	163/207[2]
N, N & T or H & T	550/700	310[3]	13	30	152/201[2]
H & T	700/850	495	11	25	201/255[2]
H & T	850/1000	585	11	15	248/302[2]
H & T	1000	880	9	30	269/321[2]
H & T	1160	1000	5	10	341/388[2]
H & T	620/770	480	14	25	179/223[2]
N or N & T	540	245[3]	15	—	—

Table 26.41a INVESTMENT CASTINGS—CARBON AND LOW ALLOY STEELS

Grade BS 3146 Part 1	*Description of steels*	*Composition (maxima unless stated)* C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
CLA9	C Steel for case hardening	0.10/0.18	0.20/0.60	0.60/1.00	0.035	0.10[4]	0.40[4]	Cu 0.30[4]	
CLA10	3 Ni for case hardening	0.10/0.18	0.20/0.60	0.30/0.60	0.035	0.30[4]	0.10[4]	2.75/3.50	Cu 0.30[4]
CLA11	3 Cr Mo for nitriding	0.20/0.30	0.30/0.80	0.30/0.60	0.035	2.90/3.50	0.40/0.70	0.40[4]	Cu 0.30[4] Sn 0.03[4] V 0.02[4]
CLA12-A &B	Cr for abrasion resisting	0.45/0.55	0.30/0.80	0.50/1.00	0.035	0.80/1.20	0.10[4]	0.40[4]	Cu 0.30[4]
-C	Ni Mo for case	0.55/0.65	0.30/0.80	0.50/1.00	0.035	0.80/1.50	0.20/0.40	0.40[4]	Cu 0.30[4]
CLA13	hardening	0.12/0.20	0.20/0.60	0.30/0.70	0.035	0.30[4]	0.20/0.30	1.50/2.00	Cu 0.30[4]

Notes:
1 Residual elements—total not to exceed 0.80%
2 When specifically requested
3 For information only
4 Residuals

Table 26.41b INVESTMENT CASTINGS- CORROSION AND HEAT RESISTING STEELS

Grade BS 3146 Part 2	*Description of steels*	*Composition (maxima unless stated)* C	Si	Mn	P & S	Cr	Mo	Ni	*Others*
ANC1-A		0.15	0.20/1.20	0.20/1.00	0.035[1]	11.5/13.5	—	1.00	—
-B	13 Cr	0.12/0.20	0.20/1.20	0.20/1.00	0.035[1]	11.5/13.5	—	1.00	—
-C	Martensitic	0.20/0.30	0.20/1.20	0.20/1.00	0.035[1]	11.5/13.5	—	1.00	—
ANC2	18 Cr 2 Ni Martensitic	0.12/0.25	0.20/1.00	0.20/1.00	0.035	15.5/20.0	—	1.50/3.00	—
ANC3-A	18 Cr 10 Ni	0.12	0.20/2.00	0.20/2.00	0.035[1]	17.0/20.0	—	8.00/12.0	—
	Austenitic	0.12	0.20/2.00	0.20/2.00	0.035[1]	17.0/20.0	—	8.50/12.0	Nb 8 × C/ 1.10
ANC4-A	18 Cr 11 Ni	0.08	0.20/1.50	0.20/2.00	0.035[1]	18.0/20.0	3.00/4.00	11.0/14.0	—
-B	3 Mo	0.08	0.20/1.50	0.20/2.00	0.035[1]	17.0/20.0	2.00/3.00	10.0 min	—
-C	Austenitic	0.12	0.20/1.50	0.20/2.00	0.035[1]	17.0/20.0	2.00/3.00	10.0 min	Nb 8 × C/ 1.10
ANC5-A		0.50	0.20/3.00	0.20/2.00	—	22.0/27.0	—	17.0/22.0	—
-B	Ni Cr Steels	0.50	0.20/3.00	0.20/2.00	—	15.0/25.0	—	36.0/46.0	—
-C		0.75	0.20/3.00	0.20/2.00	—	10.0/20.0	—	55.0/65.0	—
ANC6-A		0.15/0.30	0.75/2.00	0.20/1.00	0.035	20.0/25.0	—	55.0/65.0	—
-B	Cr–Ni Steels	0.15/0.30	0.75/2.00	0.20/1.00	0.035	20.0/25.0	—	10.0/15.0	W 2.50/ 3.50
-C		0.05/0.15	0.75/2.00	0.20/1.00	0.035	20.0/25.0	—	10.0/18.0	W 2.50/ 3.50
ANC20 A&B	14 Cr 5 Ni 2 Cu 1 Mo	0.07	0.20/2.00	0.20/1.00	0.025	12.5/15.5	0.50/2.50	3.00/6.00	Cu 1.00/ 3.50 Nb 0.50
ANC21	26 Cr 5 Ni 3 Cu 2 Mo	0.05	0.75	0.75	0.050	25.0/27.0	1.75/2.25	4.75/6.00	Cu 2.75/ 3.25 N 0.10
ANC22 A, B & C	16 Cr 4 Ni 3 Cu	0.06	1.00	0.70	P 0.035 S 0.030	15.5/16.7	—	3.60/4.60	Cu 2.80/ 3.50 Nb+Ta 0.15/0.40 N 0.05

ANC 8-19 are specialised high alloy nickel and cobalt base castings— BS 3147 Part 3: 1976 are also very high alloy castings including Ni and Co base casting—for details *see* British Investment Casters Technical Association

1 Where specified S may be as high as 0.3% in free machining grades

Treatment	*Tensile strength* R_m MPa	$R_{p0.2}$ MPa	*El % on* $5.65\sqrt{S_0}$	*Impact Izod* ft. lbf	*Hardness* HB
C or N	495[5]	215[3,5]	15[5]	20[5]	—
C or N	700[5]	350[3,5]	14[5]	30[5]	—
H & T	850/1000	600	8	15	248/302[2]
N & T or H & T	700[6]	—	8[6]	—	207[6,7] min
N & T or H & T	—	—	—	—	341 min
C or N	700[5]	350[3,5]	14[5]	30[5]	—

5 Properties quoted are for the final heat treated condition
6 Grade A only
7 Grade B hardness 293 HB min
8 Properties minima unless stated
9 N—Normalised, T-tempered, H&T—hardened & tempered, C—As cast

	Tensile strength R_m MPa	$R_{p0.2}$ MPa	*El % on* $5.65\sqrt{S_0}$	*Impact Izod* ft. lbf	*Hardness* HB
H & T	540	340[3]	15	—	152/207
H & T	620	415[3]	13	—	183/229
H & T	695	435[3]	11	—	201/255
H & T	850/1000	630[3]	8	—	248/320
ST	460	200	20	—	—
ST	460	200	20	—	—
ST	500	210[3]	12	—	—
ST	500	210[3]	12	—	—
ST	500	210[3]	12	—	—
C	—	—	—	—	—
C	—	—	—	—	—
C	—	—	—	—	—
C	460[2]	—	17[2]	—	—
C	460[2]	—	17[2]	—	—
C	460[2]	—	17[2]	—	—
PH (A)	950/1200	800	12	15	—
PH (B)	1250/1500	950	8	8	—
C	700	500	18	10	—
PH (A)	1230	1030	8	—	361[2]
PH (B)	1030	895	8	—	313[2]
PH (C)	900	830	8	—	294[2]

2 When specifically requested
3 For information only
4 Properties minima unless stated
5 H & T—Hardened and tempered, ST—solution treated, C—as cast, PH—precipitation hardened

26.9 Cast irons

Data Source BCIRA.

26.9.1 Classification of cast irons

Cast irons may be divided into two main groups, comprising the general purpose grades which are used for the majority of engineering applications and the special purpose or alloy cast irons which are used where the operating conditions involve extremes of heat, corrosion or abrasion.

26.9.2 General purpose cast irons

These materials may be further classified into four groups, depending on the graphite form.

British Standards specifications exist for each of these materials. New metric specifications incorporating SI units are available for malleable, grey and nodular irons. The grade number denotes the tensile strength and the % elongation, e.g. BS 2789 Grade 400/18 has a minimum tensile strength of 400 MPa and a minimum elongation of 18%. In the case of grey irons, which all fail with an elongation less than 1%, the grade number denotes tensile strength only in test specimens of standad dimensions.

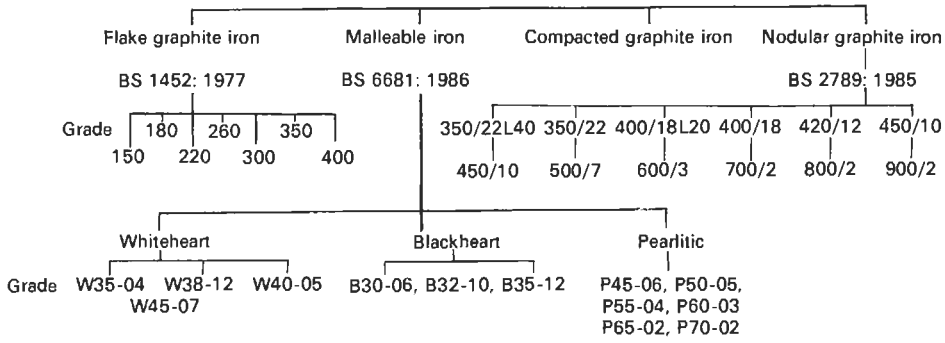


Figure 26.1 *Classification of general purpose cast irons*

GREY IRONS

The grade number denotes the minimum tensile strength requirement on a test piece machined from a 30 mm (1.2 in) diameter as-cast bar and this, rather than analysis, is the basis for specification of cast irons for engineering purposes.

For unalloyed irons the main constituents influencing tensile strength are carbon, silicon and phosphorus. Their combined effect may be expressed as a carbon equivalent value (CEV), where

$$\text{CEV} = \text{total carbon \%} + \frac{\text{phosphorus \%} + \text{silicon \%}}{3}$$

Typical analysis and CEVs are given in Table 26.47.

Table 26.42 TYPICAL ANALYSES OF GREY IRONS

BS grade	150	180	220	260	300	350	400
Total carbon %	3.1–3.4	3.2–3.5	3.2–3.4	3.0–3.2	2.9–3.1	3.1 max.	2.9 max.
Silicon % (final)	2.5–2.8	2.2–2.5	2.0–2.5	1.6–1.9	1.5–1.8	1.4–1.6	1.4–1.6
Manganese %	0.5–0.7	0.5–0.8	0.6–0.8	0.6–0.8	0.5–0.7	0.6–0.75	0.6–0.75
Sulphur % (max.)	0.15	0.15	0.15	0.15	0.12	0.12	0.12
Phosphorus %	0.9–1.2	0.6–0.9	0.1–0.5	0.3 max	0.2 max	0.15 max	0.15 max
Chromium %	—	—	—	—	0.4–0.6	—	—
Nickel %*	—	—	—	—	0.8–1.5	1.5	2.0
Molybdenum %	—	—	—	—	—	0.3–0.5	0.5–0.6
CEV	4.5–4.55	4.3–4.35	4.1–4.2	3.8–3.9	3.5–3.6	—	—

* Copper may be used partially to replace nickel.

Grey irons are section sensitive, their structure and mechanical properties depending on cooling rate in the mould, which in turn depends to a first approximation on section thickness. This effect is shown in Figure 26.2, with tensile and test bar diameter requirements in Table 26.48.

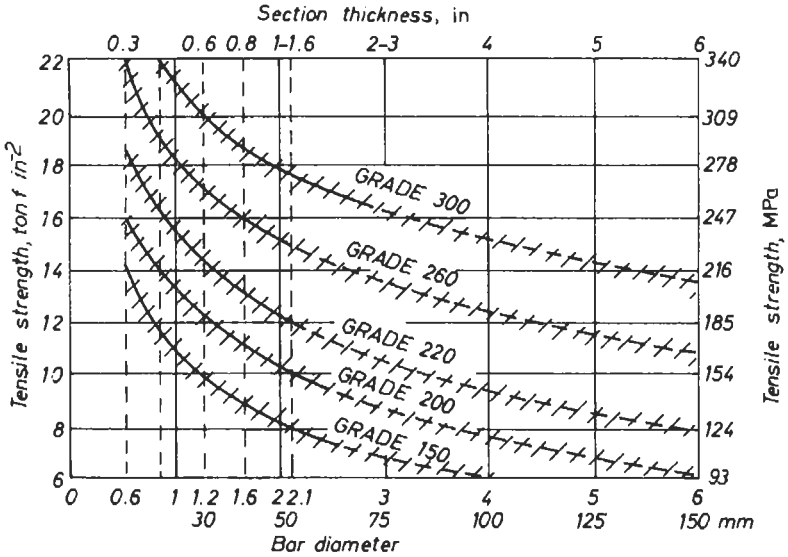


Figure 26.2 *Variation of tensile strength with section thickness*

Table 26.43 SPECIFIED PROPERTIES OF GREY IRONS

Cross-sectional thickness of casting represented	*Diam. of as-cast bar*	*Gauge diam.*	*Grade* *Minimum tensile strength*						
			10	12	14	17	20	23	26
mm (in)	mm (in)	mm (in)	MPa (tonf in^{-2})	MPa (tonf in^{-2})	MPa (tonf in^{-2})	MPa (tonf in^{-2})	MPa (tonf in^{-2})	MPa (tonf in^{-2})	MPa (tonf in^{-2})
Up to 9.5 (up to $\frac{3}{8}$)	15.2 (0.6)	10.1 (0.399)	170 (11.0)	201 (13.0)	247 (16.0)	294 (19.0)	340 (22.0)	386 (25.0)	432 (28.0)
9.5–19.0 ($\frac{3}{8}$–$\frac{3}{4}$)	22.2 (0.875)	14.3 (0.564)	162 (10.5)	193 (12.5)	232 (15.0)	278 (18.0)	324 (21.0)	371 (24.0)	417 (27.0)
19.0–29.6 ($\frac{3}{4}$–$1\frac{1}{8}$)	30.5 (1.2)	20.3 (0.798)	154 (10.0)	185 (12.0)	216 (14.0)	262 (17.0)	309 (20.0)	355 (23.0)	402 (26.0)
29.6–41.3 ($1\frac{1}{8}$–$1\frac{5}{8}$)	40.6 (1.6)	28.6 (1.128)	147 (9.5)	178 (11.5)	209 (13.5)	247 (16.0)	294 (19.0)	340 (22.0)	386 (25.0)
over 41.3 (over $1\frac{5}{8}$)	53.3 (2.1)	37.9 (1.493)	139 (9.0)	170 (11.0)	201 (13.0)	232 (15.0)	278 (18.0)	324 (21.0)	371 (24.0)

Excessive rates of cooling lead to the formation of free carbides, or chilling. This effect is more severe with the higher strength irons, and occurs first at free edges of castings, where the cooling rate is a maximum, as shown in Table 26.49.

Table 26.44 CHILLING TENDENCY IN DIFFERENT GRADES OF IRON

BS grade	150	180	220	260	300
Approximate minimum chill free edge					
(in)	0.1–0.2	0.2–0.3	0.25–0.4	0.4–0.65	0.6–1.1
(mm)	2.5–5.0	5.0–7.5	6.3–10.0	10.0–16	15–30

Inoculation of high duty grey irons, from Grade 260 to 400, is carried out using a technique in which a small amount of inoculant, usually containing silicon, is added to the metal immediately before pouring so as to increase the silicon content by 0.3–0.5%. Some commonly used inoculants include ferrosilicon, calcium silicide, SMZ (silicon–manganese–zirconium). Graphite is also a powerful inoculant. Several other proprietary inoculants, most of which are based on one or more of these substances, are also effective. The efficiency of a graphite inoculant depends on high purity, but that of other types depends on the presence of minor constituents such as aluminium, calcium, barium, strontium and cerium.

The tensile strength of hypo-eutectic grey irons (i.e. CEV less than 4.3) can be significantly increased by inoculation, particularly with silicon-containing inoculants. When the CEV is in the range 3.9–4.1 maximum strength is obtained when the inoculant adds 0.2–0.3% silicon, corresponding to an increase of approximately 15 MPa (1 tonf in^{-2}) compared with uninoculated material. With CEV below 3.9 the addition of inoculant sufficient to give a 0.5% increase in silicon content can add up to 60 MPa (4 tonf in^{-2}) to the tensile strength, the effect being progressive with increasing additions up to at least this level.

The chilling tendency of grey irons is also reduced by inoculation, enabling significantly thinner chill free sections than those in Table 26.50 to be cast. The effect is progressive up to at least 0.4% of added silicon.

Table 26.45 ANALYSES OF PIG IRONS

	Typical composition				
	TC %	Si %	Mn %	S % *max*	P %
Hematite	3.7–4.5	0.5–3.5	0.5–1.2	0.05	0.05 max
Low phosphorus	3.8–4.2	1.0–4.5	0.7–1.1	0.05	0.065 max
	3.8–4.2	1.0–4.5	1.1–1.5	0.05	0.065 max
	3.8–4.2	1.0–4.5	1.5–2.0	0.05	0.065 max
Medium phosphorus	3.5–4.0	2.0–3.5	0.8–1.0	0.05	0.5–0.7
High phosphorus	3.3–3.8	2.0–4.5	0.6–0.8	0.05	0.7–1.2
	3.3–3.8	2.0–4.5	0.8–1.2	0.05	0.7–1.2

The chill reducing effect forms the basis for most control tests for inoculation. A sand cast wedge or a small block cast in sand with one face against a metal plate may be made from the metal before and after inoculation. The test pieces are then fractured and the change in depth of chill measured as an assessment of the success of the treatment. Typical results are illustrated in Figure 26.3.

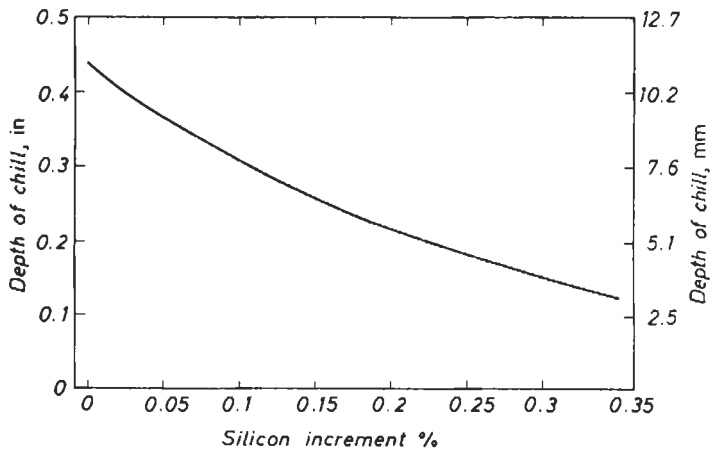


Figure 26.3 *Effect of inoculation on chill depth*

In castings which are susceptible to shrinkage defects inoculation will accentuate these problems, and its use should be restricted only to those castings where chilling or strength considerations make it necessary.

Charge materials for production of grey irons include pig irons, cast iron scrap, steel scrap and ferro alloys.

The main purposes served by pig irons is the provision of carbon, silicon, manganese and, where required, phosphorus and alloying elements. They also limit the sulphur content of cupola melted iron.

Blast furnace pig irons are available in a variety of grades which differ mainly in phosphorus content. Each grade is generally available within different ranges of silicon and manganese contents.

The carbon content will generally be at the lower end of the above ranges when the silicon content is at the upper end of the corresponding range. The silicon content can be specified in increments of 0.25 or 0.50% within the ranges given.

Refined alloy and special pig irons are produced to the customer's specific requirements in a wide range of compositions. They may contain alloying elements if required, within specified ranges of alloy content.

Silvery pig iron (10–12% silicon, 12–14% silicon) provides silicon in a more dilute form than ferrosilicon. It is used to minimise variation in silicon content of cupola melted iron when a substantial quantity of silicon is added, and to reduce the risk of aluminium contamination of the metal which may arise if large additions of ferrosilicon are made.

Special irons, generally of high carbon content, but with a very low content of residual elements are also available, their main use being for the production of nodular graphite iron.

Return scrap is the best source of scrap for re-melting providing this is of known and consistent composition and this should be fully utilised.

Purchased scrap is available in several fairly readily identifiable types as given in Table 26.51.

In comparison with pig iron and cast iron scrap, steel scrap is low in carbon and silicon contents, and the phosphorus and sulphur contents are generally below 0.05%. It is used to lower carbon and silicon contents, particularly in the production of higher strength irons.

Ferro-alloys are used to remedy deficiencies of certain elements, particularly silicon and manganese in the charges.

Table 26.46 COMPOSITION OF SCRAP

	Approximate composition %				
Type of scrap	C	Si	Mn	S	P
Light section scrap, usually less than $\frac{1}{4}$ in thick	3.2–3.5	2.2–2.8	0.5–0.7	0.10–0.15	1.0–1.5
Textile and machine scrap, generally up to $1\frac{1}{2}$ in average section	3.0–3.3	1.8–2.2	0.5–0.8	0.10–0.15	0.5–1.0
Railway chairs	2.8–3.5	1.5–2.5	Up to 0.5	Up to 0.25	1.0–1.5
Automobile engine scrap	3.1–3.3	2.0–2.2	0.5–0.8	0.08–0.15	<0.2
Ingot mould scrap (heavy section)	3.5–3.8	1.4–1.8	0.5–1.0	0.08	<0.1
Blackheart malleable scrap	2.2–3.1	1.3–1.6	0.3–0.6	0.09–0.25	0.06–0.08
Whiteheart malleable scrap	0.2–2.3	0.5–0.8	0.2–0.3	0.15–0.25	0.06–0.08

FERROSILICON

The two most common grades, in lump form, contain 75–80% and 45–50% of silicon.

Ferromanganese in lump form contains 75–80% manganese.

BRIQUETTES

For relatively small additions of silicon, manganese and chromium, briquettes may be used for convenience and consistency. They contain a fixed amount of the alloy and avoid the necessity of weighing the addition.

Table 26.47 LOSSES OF ALLOYING ELEMENTS

	Melted in cupola	*Added to ladle*
Copper	0 of amount charged	0
Nickel	0 of amount charged	0
Molybdenum	0–5% of amount charged	5% of amount added
Manganese	20–30% of amount charged	5–10% of amount added
Chromium	10% of amount charged	15% of amount added
Silicon	10–15% of amount charged	10% of amount added

Table 26.48 SUMMARY OF STRUCTURAL EFFECTS OF ALLOYING ELEMENTS ON CAST IRON

Element	*% used in pearlitic irons*	*'Chill'*	*Effect on carbides (at high temps.)*	*Effect on graphite structure*	*Effect on combined carbon in pearlite*	*Effect on matrix*
Chromium chill inducing	0.15–0.5	Increases*	Strongly stabilizes	Mildly refines	Increases	Refines pearlite
Vanadium	0.15–0.3	Increases	Strongly stabilizes	Refines	Increases	and hardens
Boron	—	Strongly increases	—	—	—	—
Manganese mildly chill inducing	0.3–1.25	Mildly increases	Stabilizes	Mildly refines	Increases	Refines pearlite and hardens
Molybdenum	0.3–1.0	Mildly increases	About neutral	Strongly refines	Mildly increases	Refines pearlite and strengthens
Tin	0.1–0.2	About neutral	About neutral	About neutral	Increases	
Copper mildly chill restraining	0.5–2.0	Mildly restrains	About neutral	About neutral	Mildly decreases	Hardens
Carbon chill restraining	—	Strongly restrains	Decreases stability	Coarsens	Strongly decreases	Produces ferrite and softens
Silicon	—	Strongly restrains	Decreases stability	Coarsens	Strongly decreases	Produces ferrite and softens
Aluminium	—	Strongly restrains	Decreases stability	Coarsens	Strongly decreases	Produces ferrite and softens
Nickel	0.1–3.0	Restrains†	Mildly decreases stability	Mildly refines	Mildly decreases and stabilizes at eutectoid	Refines pearlite and hardens
Titanium	0.05–0.10	Restrains†	Decreases stability	Strongly refines‡	Decreases	Produces ferrite and softens
Zirconium	0.10–0.30	Restrains†	—	About neutral	—	Produces ferrite and softens

* Chill inducing effect of 1 part of chromium about balances chill restraining effect of 1½ parts silicon or 2½ parts nickel.
† Chill restraining effect of nickel about half that of silicon.
‡ Strong refining action of titanium takes place when small amounts are added, particularly when oxygen is also present.

Table 26.49

Element	*Graphitizing value* (Si = 1)	*Element*	*Graphitizing value* (Si = 1)
Aluminium	0.5	Manganese	−0.25
Copper	0.35	Molybdenum	−0.35
Nickel	0.3–0.4	Chromium	−1.2

Melting range varies widely with composition, the melting temperature falling with increase of carbon content so that low carbon irons must be cast at considerably higher temperatures than high carbon irons. With grey irons containing high phosphorus, melting of the steadite (phosphide eutectic) begins at about 960°C, giving a relatively long melting range.

FLUIDITY OF CAST IRON

The fluidity of cast iron depends primarily upon composition and pouring temperature. The fluidity, as measured by a special test spiral casting, may be improved by increasing the carbon, silicon or phosphorus contents, or by increasing the pouring temperature. Of these variables, carbon content is the most effective from the point of view of composition, but an increase of 15–20°C in the pouring temperature improves the fluidity as much as an increase of 0.10% carbon, 0.30% silicon or 0.20% phosphorus.

Table 26.50 DENSITIES AND LIQUIDIS TEMPERATURES OF SOME TYPICAL GREY CAST IRONS (BASED ON 3.8 cm (1½ in) SECTION)

	Iron number						
	1	2	3	4	5	6	7
Density, g cm^{-3} (room temperature)	7.02	7.09	7.26	7.03	7.08	7.27	7.14
Density, g cm^{-3} (liquidus)	6.90	6.94	6.92	6.89	6.89	6.92	6.89
Liquidus temperature, °C	1 150	1 150	1 250	1 150	1 155	1 250	1 195
Liquid contraction per 100°C(%)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Composition, %							
Total carbon	3.69	3.67	3.10	3.39	3.27	3.08	2.90
Graphitic carbon	3.53	3.26	2.31	3.20	2.88	2.18	2.68
Silicon	2.87	2.10	1.69	2.86	2.87	1.68	2.88
Phosphorus	0.68	0.46	0.35	0.67	0.59	0.35	0.66
Manganese	0.59	0.54	0.48	0.58	0.52	0.44	0.44
Sulphur	0.03	0.05	0.04	0.03	0.03	0.04	0.03

Table 26.51 HARDNESS AND DENSITY OF MICRO-CONSTITUENTS OF CAST IRON

Constituent	*Density* g cm^{-3}	*Brinell hardness No.*	*Remarks*
Ferrite	7.86	70–75	Iron (electrolytic)
Silico-ferrite	—	88	Containing 0.82% silicon
Silico-ferrite	—	124	Containing 2.28% silicon
Silico-ferrite	—	150	Containing 3.4% silicon
Pearlite	7.846	240	—
Pearlite (silico-ferrite and cementite)	—	200–450	Depending on interlamellar distance
Graphite	2.55	—	—
Ledeburite (massive cementite and sat. austenite)	—	680–840	—
Steadite	7.32	—	—
Manganese sulphide	4.00	—	—
Iron sulphide	5.02	—	—
Divorced pearlite	—	130–150	—
Phosphide eutectic	—	—	400–600 HV
Iron carbide Fe_3C or $(FeCr)_3C$	7.66	550	800–1 200 HV
Iron carbide $(CrFe)_7C_3$	—	—	1 300–1 800 HV

Table 26.52 SPECIFIC GRAVITY OF TYPICAL IRONS OF BRITISH STANDARDS GRADES (BS 1452)

Grade	*Up to* 180	220	260	300	350	400
Specific gravity	6.8–7.15	7.2–7.3	7.25–7.35	7.3–7.4	7.3–7.4	7.4–7.6

Heat treatment of grey cast irons may be carried out to eliminate residual stresses, improve machinability or to increase wear resistance.

Stress relief heat treatment is carried out by slow heating at 50–100 °C per hour to 600 °C ± 10 °C, holding at 600 °C for one hour plus an additional half hour per cm (0.4 in) of maximum section thickness, and cooling at 50–100 °C per hour to below 200 °C followed by air cooling.

Annealing heat treatment is applied when improved machinability is required. There are two distinct sets of conditions in which annealing may be carried out.

1. To break down free carbide or chill formed as a result of failure to match carbon equivalent value to minimum free edge thickness. Annealing must then be carried out at 900 °C for 1–5 h to ensure complete breakdown of carbide, followed by air cooling to ensure a pearlitic matrix. This treatment is carried out as an emergency measure to salvage otherwise unmachinable castings.
2. To provide castings which can be machined at a very high rate. Castings which are fully pearlitic can be annealed to give a mainly ferritic matrix with a hardness of 140–180 HB by holding at 780–820 °C for 1–2 h followed by slow cooling.

Hardening by quenching and tempering is carried out where high surface hardness is required, with corresponding improvement in wear resistance. Hardening temperatures in the range 850–880 °C are used, followed by oil quenching and tempering at 300 °C to reduce internal stresses. Tensile strength is not increased to the same extent as hardness (Figure 26.4) and because of the risk of cracking during quenching, this process is usually restricted to small castings of simple shape.

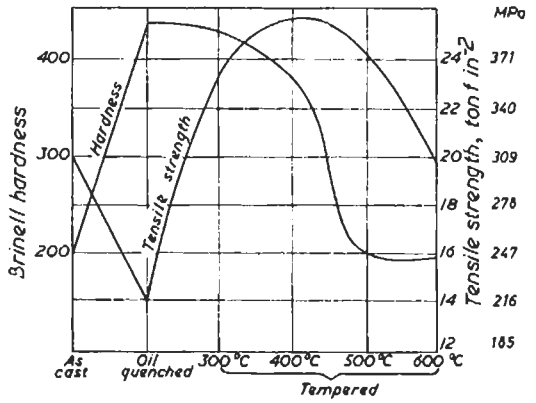


Figure 26.4 *Effect of heat treatment on the strength and hardness of alloy cast iron*

Surface hardening, by flame or induction heating, is widely used to improve the wear resistance of critical surfaces on large castings such as slideways on machine tools. For good response to this treatment the as-cast structure must be fully pearlitic, and the phosphorus content must be below 0.2% to avoid pitting. Hardness in the range 450–500 HV are obtained with depths of 1–3 mm (0.040–0.125 in).

MALLEABLE IRONS

Malleable irons are brittle as cast, their structure consisting of iron carbide in a pearlitic matrix. By suitable heat treatment the carbides are broken down resulting in a structure that consists of graphite aggregates (temper carbon) in a matrix which may be ferritic or pearlitic, depending on composition and heat treatment conditions

The British Standards (BS 309, 310 and 3333) specify neither composition (apart from maximum phosphorus content of 0.12%) nor heat treatment.

Table 26.53 MECHANICAL PROPERTIES OF WHITEHEART MALLEABLE IRON

Grade BS 6681: 1986	*Diameter of test bar d.* mm†	*Tensile strength min.* R_m MPa	0.2 *Proof stress min.* $R_{p0.2}$ MPa	*Elongation min. A* %	*Hardness typical max* HB
W35-04	9	340	—	5	230
	12	350	—	4	
	15	360	—	3	
W38-12*	9	320	170	15	200
	12	380	200	12	
	15	400	210	8	
W40-05	9	360	200	8	220
	12	400	220	5	
	15	420	230	4	
W45-07	9	400	230	10	220
	12	450	260	7	
	15	480	280	4	

* Although all grades of whiteheart malleable are weldable with correct procedure, W38-12 should be selected where strength and avoidance of post weld heat treatment is required.

† Test bar diameter should be representative of the important sectional thickness of the casting.

Ref. British Cast Iron Research Association.

In practice, whiteheart malleable irons have an initial total carbon content of about 3.5% which is reduced to the range 0.25–2.0% by heat treating the castings at 900°C in an oxidizing environment, and slowly cooling. The required conditions may be produced by packing the castings in an oxidizer (e.g. hematite ore) or by use of a controlled atmosphere furnace. This results in a carbon gradient within the castings, the outer layer being normally ferritic and graphite-free while the core structure consists of temper carbon aggregates in a pearlitic matrix. Small castings of thin section may have a fully decarburized structure throughout, and this is sometimes referred to as a weldable grade of malleable iron.

Blackheart and pearlitic malleable irons have a lower initial total carbon content in the range 2–3%. Heat treatment in a neutral atmosphere at 850–875°C followed by slow cooling results in a uniform structure of temper carbon in a ferritic matrix.

Malleable irons Pearlitic have a structure consisting of temper carbon in a pearlitic matrix. This is produced either by fapid cooling after annealing or by the addition of 0.5% or more manganese. Pearlitic malleable irons have a good response to surface hardening by flame or induction heating, and hardness values of HV 500 can be consistently achieved in production.

NODULAR IRONS

In nodular (spheroidal graphite) irons free graphite is present as spheres or nodules in the as-cast condition. Graphite in this form has a much smaller weakening effect on the matrix than the dispersed graphite flakes in grey ions. Nodular irons therefore have considerably higher strength, ductility, and impact values than grey irons.

Cerium and magnesium additions both produce nodular structures, but the latter has been found to be more adaptable and economical. Both elements are desulphurizers and nodule formation is not possible until the sulphur content has been lowered to about 0.02%. Very small amounts of trace elements, such as 0.003% bismuth, 0.004% antimony, 0.009% lead and 0.12% titanium prevent nodule formation. The effect of these elements is additive, but it can be neutralized by the addition of sufficient cerium to give a residual content of 0.005–0.01%.

Magnesium may be added directly to the ladle as nickel–magnesium, nickel–silicon–magnesium or iron–silicon–magnesium alloy. Higher magnesium recovery is obtained using a plunging technique in which lower density, higher magnesium content additions such as magnesium impregnated coke are held below the liquid metal surface by means of a plunging head. Maximum recovery results from the addition of pure magnesium to the molten iron in a closed pressure-tight converter vessel. Because of equipment costs the use of this latter method is normally restricted to large-scale production.

In all cases the amount of magnesium to be added is given by:

$$\text{Mg} = \frac{\frac{3}{4}\,(\text{initial sulphur content}) + \text{residual magnesium content (usually 0.03–0.05\%)}}{\text{expected magnesium recovery}}$$

Nodular irons are inoculated with 0.4–0.8% silicon after nodulizing to refine the structure and minimize chilling.

The carbon content of nodular irons is usually kept above 3.5% in the interests of good castability. Silicon, manganese and phosphorus should be below 2.3%, 0.4% and 0.06% respectively to give maximum ductility and impact value in the ferritic condition.

Nodular irons are slightly more prone to shrinkage defects than grey irons.

Adequate feed metal should be provided and moulds of high rigidity are to be preferred. Running systems should be designed to minimize turbulence, so as to prevent the entrapment of dross which tends to be formed as a result of the magnesium content.

Although nodular irons are much less section sensitive than grey irons, depending on the trace amounts of carbide stablizing elements present, their matrix structures may range from fully pearlitic to completely ferritic, and chilling may occur in sections thinner than 5 mm (0.2 in).

By close control of analysis and inoculation practice nodular irons can be produced in the as-cast condition over a wide range of section thicknesses with any required matrix structure from fully ferritic to fully pearlitic.

Alternatively, the matrix structure of nodular iron castings can be modified by appropriate heat treatments, since the presence of free carbon in the form of graphite enables diffusion of carbon to or from the graphite particles to take place. This is not possible with steels, which contain no free graphite. The effect of variation in matrix structure on mechanical properties is much more pronounced with nodular iron than with flake graphite cast iron, and by heat treatment of an iron of fixed composition foundries can produce castings conforming to the complete range of the grades of BS 2789: 1985.

Practical heat treatments include:

Annealing Heat to 850–900°C where the matrix becomes completely austenitic and slow furnace cool at 20–35°C per hour to below 700°C. Alternatively, cool more rapidly to 700–720°C and hold for 4–12 h, followed by air cooling. Ferritic iron produced in this way confirm to BS 2789: 1985 grades 350/22 to 420/12.

Normalizing This is carried out by air cooling from 850 to 900°C, and produces a mainly pearlitic matric conforming to grades 700/2 and 800/2 in castings of light and medium section. The use of alloying elements is often necessary to produce a pearlitic matrix in heavier section castings.

Hardened and tempered structures These are produced by oil quenching from 850 to 900°C and tempering at 550–600°C. Material conforming to BS 2789 Grade 800/2 and 900/2 is sometimes inveriably produced by this method.

Austempering is carried out by heating castings to 850–950°C, followed by quenching to an isothermal treatment temperature within the range 230–400°C and holding this temperature typically for 1–2 hours. A variety of bainitic structures can be obtained, resulting in combinations of strength, ductility and toughness which cannot be achieved in ductile irons by other means. These austempered ductile irons (ADI) are used for many different engineering applications such as gears, crankshafts, vehicle suspension components and parts of earthmoving equipment. Provisional specifications for

Table 26.54 MECHANICAL PROPERTIES OF BLACKHEART MALLEABLE IRON

Grade BS 6681: 1986	*Diameter of test bar d.* mm	*Tensile strength min.* R_m MPa	0.2% *Proof stress* $R_{p0.2}$ *min.* MPa	*Elongation min.* %	*Hardness typical max* HB
B30-06	12	300	—	6	150
	15	300	—	6	
B32-10	12	320	190	10	150
	15	320	190	10	
B35-12	12	350	200	12	150
	15	350	200	12	

Ref British Cast Iron Research Association.

Table 26.55 MECHANICAL PROPERTIES OF PEARLITIC MALLEABLE IRON

Grade BS 6681: 1986	*Diameter of test bar d.* mm	*Tensile strength min.* R_m MPa	0.2% *Proof stress* $R_{p0.2}$ *min* MPa	*Elongation min* %	*Hardness typical* HB
P45-06	12	450	270	6	150/200
	15	450	270	6	
P50-05	12	500	300	5	160/220
	15	500	300	5	
P50-04	12	550	340	4	180/230
	15	550	340	4	
P60-03	12	600	390	3	200/250
	15	600	390	3	
P65-02	12	650	430	2	210/260
	15	650	430	2	
P70-02*	12	700	530	2	240/290
	15	700	530	2	

* If air quenched and subsequently tempered min 0.2% proof stress 530 MPa min.
Ref. British Cast Iron Research Association.

various countries to cover ADIs are summarised in Table 26.57. The various grades can be typically produced from the same ductile iron by adjustment of the austempering time and temperature.

ADI exhibits section size sensitivity and test bars are not representative of heavy sections. At −40°C high toughness grades may show a drop of 15% in yield strength as well as a drop in tensile strength compared with room temperature values. No changes have been found in elevated temperature properties up to 300°C. Also of concern is the low temperature toughness and the ductile–brittle transformation temperature although notched specimen results indicate gradual toughness transition as temperature decreases.

Mixed matrix structures Structures intermediate between the annealed and normalized grades have a range of mechanical properties depending on the ratio of ferrite to pearlite. The corresponding grades of BS 2789 are 400/10, 500/7 and 600/3. In practice these structures are produced by austenitizing at 850–900°C followed by either controlled rapid cooling at lapproximately 100°C per hour through the critical temperature range of 720–800°C or by rapid air cooling from an appropriate intermediate temperature, e.g. 730°C, within the critical range.

26.9.3 Compacted graphite irons

Although the existence of compacted graphite containing irons has been known for many years, it is only relatively recently that they have been commercially exploited. Such irons are characterised by the graphite being present in the form of relatively short, thick flakes with rounded extremities and undulating surfaces.

In general compacted graphite irons have mechanical and physical properties intermediate between those of conventional flake graphite irons (grey irons) and nodular graphite irons. The outstanding characteristics are good thermal conductivity combined with useful ductility and higher tensile and fatigue strengths than for grey irons.

At present no British Standard exists for these materials.

The presence of certain element combinations in irons which would otherwise solidify with a conventional flake graphite form may promote the formation of the compacted type of graphite. At present the production of compacted graphite irons is largely based on additions of magnesium and/or cerium to irons of low sulphur content. The magnesium based treatments are similar to those employed for nodular graphite iron production while the cerium methods are usually simple ladle addition processes.

In the magnesium process, as the magnesium content is increased, the graphite structure changes from conventional flake, through compacted flake to fully nodular. The range of magnesium contents to facilitate compacted flake structures is very narrow and it is usually necessary to employ additions of titanium and cerium to extend the range and provide a practical ladle based process. Magnesium and titanium are usually present in the ranges 0.015–0.035 per cent and 0.08–0.15 per cent respectively with a trace of cerium.

Table 26.56 MECHANICAL PROPERTIES OF NODULAR IRONS

Grade	*Tensile strength*		*Proof stress*		*Elongation*	*Hardness*	*Impact*			*Structure*
BS 2789:	R_m *min*		$R_{p0.2}$ *min*		*A min*	HB	*Charpy V-notch J**			
1985	MPa	tonf in^{-2}	MPa	tonf in^{-2}	%		20°C	−20°C	−40°C	†
350/22L40	350	22.7	220	14.2	22	≤160	—	—	9(12)	F
350/22	350	22.7	220	14.2	22	≤160	14(17)	—	—	F
400/18/L20	400	25.9	250	16.2	18	≤179	—	9(12)	—	F
400/18	400	25.9	250	16.2	18	≤179	11(14)	—	—	F
420/12	420	27.2	270	17.5	12	≤212	—	—	—	F
450/10	450	29.1	320	20.7	10	160/221	—	—	—	F/P
500/7	500	32.4	320	20.7	7	170/241	—	—	—	F/P
600/3	600	38.9	370	240	3	192/269	—	—	—	P/F
700/2	700	45.3	420	27.2	2	229/302	—	—	—	P
800/2	800	51.8	480	31.1	2	248/352	—	—	—	For TS
900/2	900	58.3	600	38.8	2	302/359	—	—	—	TM

Notes:

Verification of hardness and 0.2% proof stress is optimal.

* Individual value. Value in brackets is mean of 3 tests.

† F = ferrite, F/P = ferrite/pearlite, P/F = pearlite/ferrite, P = pearlite, TS = tempered structure, TH = tempered martensite.

Table 26.57 MECHANICAL PROPERTIES OF AUSTEMPERED DUCTILE IRON (ADI) (PROPOSED SPECIFICATIONS)

Grade *ASTM A897M-90*	*Tensile strength* R_m *min* MPa	tonf in^{-2}	*Yield strength min* MPa	tonf in^{-2}	*Elongation A min* %	*Hardness* HB	*Impact unnotched Charpy J*
850/550/10	850	55.0	550	35.6	10	269/321	100
1050/725/7	1 050	68.0	700	45.3	7	302/363	80
1200/850/4	1 200	77.7	850	55.0	4	341/444	60
1400/1100/1	1 400	90.6	1 100	71.2	1	388/477	35
1600/1300/-	1 600	103.6	1 300	84.2	*	444/555	*
VDG(FRG)							
GGG-80B	800	51.8	500	32.4	6	250/310	—
GGG-100B	1 000	64.7	700	45.3	5	280/340	—
GGG-120B	1 200	77.7	950	61.5	2	330/390	—
GGG-140B	1 400	90.6	1 200	77.7	1	440/442	—
GGG-150B	1 500	97.1	—	—	—	421/475	—
BCIRA (GB)							
950/6	950	61.5	670	43.4	6	300/310	—
1050/3	1 050	68.0	780	50.5	3	345/335	—
1200/1	1 200	77.7	940	60.9	1	390/400	—
KYMI-KYME/ENE (FIN)							
K-9007	900	58.3	730	47.3	6	280/310	—
K-1005	1 000	64.7	800	51.8	3	300/350	—
K-12003	1 200	77.7	1 000	64.7	1	380/430	—

* Elongation and impact not specified. Grades 1400/1100/1 and 1600/1300/- mainly used for gear and wear resistant applications.

Table 26.58 A COMPARISON OF THE MECHANICAL PROPERTIES OF FLAKE, COMPACTED AND NODULAR GRAPHITE CAST IRONS IN 30 mm BAR SECTIONS

	Flake graphite iron Grade 260	*Compacted graphite iron** (*CEV* = 4.3) *Ferritic*	*Pearlitic*	*Nodular graphite iron Grade* 500/7
Tensile strength, MN/m^2	260	365	440	500
0.1% Proof stress, MN/m^2	73	260	305	323
0.2% Proof stress, MN/m^2	—	290	330	339
0.5% Proof stress, MN/m^2	—	325	365	356
Elongation %	0.57	4.5	1.5	7 min–15
Modulus of elasticity, GN/m^2	128	162	165	169
Hardness, HB 10/3000	185–226	140–155	225–245	~172

* Irons produced by magnesium-titanium-cerium treatment.

Fully compacted graphite irons have combinations of properties intermediate between those of conventional flake and nodular irons, as shown in Table 26.58. They behave elastically over a range of stresses although their limit of proportionality is lower than nodular irons. The tensile properties of compacted graphite irons are less sensitive to variations in carbon equivalent than conventional flake irons (Fig. 26.5) but they are section sensitive (Fig. 26.6).

Compacted graphite irons have intermediate thermal conductivity values between flake and nodular iron and comparative figures are given in Table 26.59.

The combination of relatively high strength and good thermal conductivity has resulted in compacted graphite irons primarily finding application where containment of stress at high temperature or under thermal cycling conditions are important. Applications for ingot moulds, cylinder heads, brakedrums and discs and manifold castings are typical.

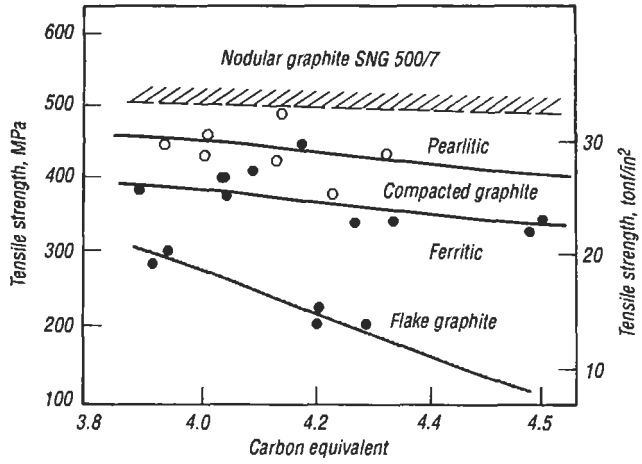


Figure 26.5 *Effect of carbon equivalent on the tensile strengths of flake, compacted and nodular graphite irons cast into* 30 mm-*diameter bars*

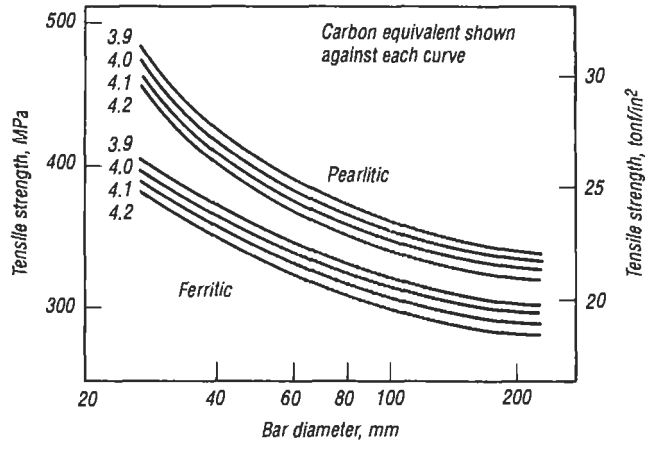


Figure 26.6 *Variation of tensile strength with cast-section size for ferritic and pearlitic compacted graphite irons of various carbon equivalents. Each curve is the centre of a band of variation in strength of about* ±30 MPa (±2 tonf/in²)

Table 56.59 A COMPARISON OF THE THERMAL CONDUCTIVITIES OF FLAKE, COMPACTED AND NODULAR GRAPHITE CAST IRONS

	Thermal conductivity W/m K				
	100°C	200°C	300°C	400°C	500°C
Flake graphite iron (Grade 17)	48.8	47.8	46.8	45.8	44.8
Compacted graphite iron (CEV ≈ 4.3)	41.0	43.5	41.0	38.5	36.0
Nodular graphite iron (Grade 500/7)	35.5	35.35	35.2	35.05	34.9

Table 26.60 AUSTENITIC CAST IRONS

Grade *BS* 3468: 1986*	*Composition %* C *max*	Si	Mn	Ni	Cr	Nb	P *max*	*Other*	*Tensile strength* R_m *min* MPa	tonf in^{-2}	*Proof strength* $R_{p0.2}$ *min* MPa	tonf in^{-2}	*Elongation* A** %
General engineering													
F1 (FG)	3.0	1.5/2.8	0.5/1.5	13.5/17.5	1.0/2.5	—	0.2	Cu 5.5/7.5	170	11.0	—	—	—
F2 (FG)	3.0	1.5/2.8	0.5/1.5	18.0/22.0	1.5/2.5	—	0.2	Cu 0.5 max	170	11.0	—	—	—
S2 (SG)	3.0	1.5/2.8	0.5/1.5	18.0/22.0	1.5/2.5	—	0.08	Cu 0.5 max	370	24.0	210	13.6	7
S2W1 (SG)	3.0	1.5/2.2	0.5/1.5	18.0/22.0	1.5/2.5	0.12/0.2	0.05	Cu 0.5 max	370	24.0	210	13.6	7
S5S (SG)	2.2	4.8/5.4	1.0 max	34.0/36.0	1.5/2.5	—	0.08 max	—	370	24.0	210	13.6	7
Special purposes													
F3 (FG)	2.5	1.5/2.8	0.5/1.5	28/32	2.5/3.5	—	0.2	Cu 0.5 max	190	13.3	—	—	—
S2B (SG)	3.0	1.5/2.8	0.5/1.5	18/22	2.5/3.5	—	0.08	Cu 0.5 max	370	24.0	210	13.6	7 (4)
S2C (SG)	3.0	1.5/2.8	1.5/2.5	21/24	0.5 max	—	0.08	Cu 0.5 max	370	24.0	170	11.0	20 (20)
S2M1 (SG)	3.0	1.5/2.8	4.0/4.5	21/24	0.5 max	—	0.08	Cu 0.5 max	420	27.2	200	13.0	25 (15)
S3 (SG)	2.5	1.5/2.8	0.5/1.5	28/32	2.5/3.5	—	0.08	Cu 0.5 max	370	24.0	210	13.6	7
S6 (SG)	3.0	1.5/2.8	6.0/7.0	12/14	0.2 max	—	0.08	Cu 0.5 max	390	25.3	200	13.0	15

* (FG)=Flake graphite, (SG)=speroidal graphite.

** Value in bracket is Charpy V notch strength at 20°C in J.

Table 26.61 ALLOY CAST IRONS

Grade	*Composition %*							*Hardness*			
BS 4844: 1986	C	Si	Mn	Ni	Cr	P *max*	*Other*	HB (*Section thickness* mm)		HV	
Low alloy grades											
1A	2.4/3.4	0.5/1.5	0.2/0.8	—	2.0 max	0.15	—	400(< 50)	350(> 50)	428(< 50)	368(> 50)
1B	2.4/3.4	0.5/1.5	0.2/0.8	—	2.0 max	0.5	—	400(< 50)	350(> 50)	428(< 50)	369(> 50)
1C	2.4/3.0	0.5/1.5	0.2/0.8	—	2.0 max	0.15	—	250(< 50)	225(> 50)	225(< 50)	205(> 50)
Nickel chromium grades											
2A	2.7/3.2	0.3/0.8	0.2/0.8	3.0/5.5	1.5/3.5	0.15	Mo 0.5	500(< 125)	450(> 125)	542(< 125)	485(> 125)
2B	3.2/3.6	0.3/0.8	0.2/0.8	3.0/5.5	1.5/3.5	0.15	Mo 0.5	550(< 125)	500(> 125)	599(< 125)	542(> 125)
2C	2.4/2.8	1.5/2.2	0.2/0.8	4.0/6.0	8.0/10.0	0.10	Mo 0.5	500(< 125)	450(> 125)	542(< 125)	485(> 125)
2D	2.8/3.2	1.5/2.2	0.2/0.8	4.0/6.0	8.0/10.0	0.10	Mo 0.5	550(< 125)	500(> 125)	599(< 125)	542(> 125)
2E	3.2/3.6	1.5/2.2	0.2/0.8	4.0/6.0	8.0/10.0	0.10	Mo 0.5	600(< 125)	550(> 125)	655(< 125)	599(> 125)
High chromium grades											
3A	1.8/3.0	1.0 max	0.5/1.5	2.0 max	14/17	0.10	Mo/Cu 2 max	600 min		655 min	
3B	3.0/3.6	1.0 max	0.5/1.5	2.0 max	14/17	0.10	Mo/Cu 2 max	650 min		712 min	
3C	1.8/3.0	1.0 max	0.5/1.5	2.0 max	17/22	0.10	Mo/Cu 2 max	600 min		655 min	
3D	2.0/2.8	1.0 max	0.5/1.5	2.0 max	22/28	0.10	Mo/Cu 2 max	600 min		655 min	
3E	2.8/3.5	1.0 max	0.5/1.5	2.0 max	22/28	0.10	Mo/Cu 2 max	600 min		655 min	
3F	2.0/2.7	1.0 max	0.5/1.5	2.0 max	11/13	0.10	Mo/Cu 2 max	600 min		655 min	
3G	2.7/3.4	1.0 max	0.5/1.5	2.0 max	11/13	0.10	Mo/Cu 2 max	650 min		712 min	

Table 26.62 CORROSION RESISTING HIGH SILICON CAST IRONS

Grade	*Composition %*						*Application*
BS 1591: 1975	C *max*	Si	Mn *max*	P *max*	S *max*	Cr	
Si10	1.2	10.0/12.0	0.5	0.25	0.1	—	Strength greater than S14
Si14	1.0	14.25/15.25	0.5	0.25	0.1	—	General corrosion
Si Cr 144	1.4	14.25/15.25	0.5	0.25	0.1	4.0/5.0	Cathodic protection anodes
Si16	0.8	16.0/18.0	0.5	0.25	0.1	—	Corrosion resistance at expense of strength

Heat treatment: Castings to be stripped from moulds while hot and as soon as possible after solidification, the hot castings to be charged to a furnace preheated to approximately 600°C and kept at this during charging. Then heat to not less than 750°C and not more than 850°C. Soak for 2 hours for castings of simple form and thickners less than 18 mm and for 8 hours for heavy castings. Cool slowly after soak to 300°C before unloading.

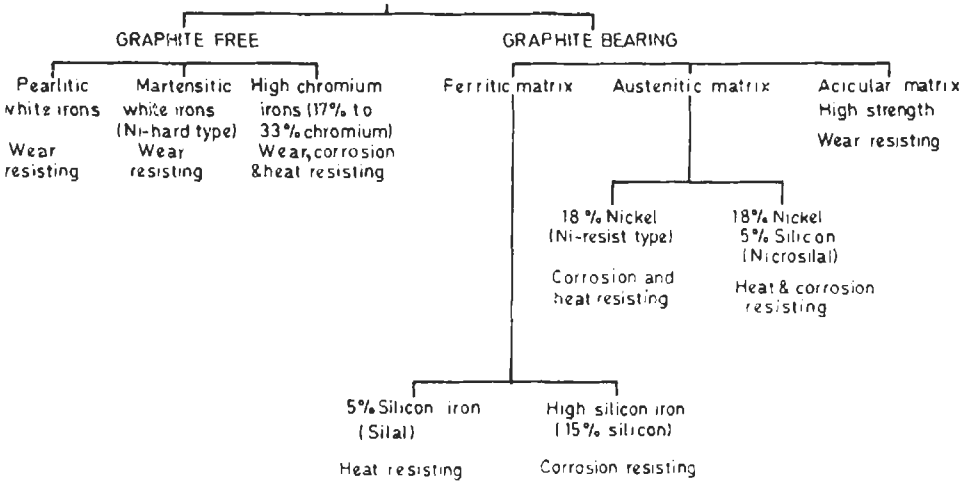


Figure 26.7 *Classification of special purpose cast irons*

British Standards are summarised for Austenitic irons BS 3468: 1986 Table 26.60, for alloy cast irons BS 4844: 1986 in Table 26.61 and for corrosion resisting high silicon irons BS 1591: 1975 in Table 26.62.

26.9.5 Applications of special purpose cast irons

HIGH TEMPERATURE

Irons in the general engineering group are suitable for applications up to at least 350°C where long-term dimensional stability is required. There are also many instances of the use of grey irons in the temperature range up to 700°C provided that appreciable growth and scaling can be tolerated.

For extended life at temperatures up to 850°C one of the alloyed irons, such as Ni-resist, Silal or Nicrosilal, may be used. The austenitic materials Ni-resist and Nicrosilal have good thermal shock resistance, but Silal is limited to applications where severe temperature gradients are absent. Above 850°C the most suitable material is 30% chromium iron, which has good oxidation resistance and a useful level of creep strength up to 1050°C.

Table 26.63 TYPICAL ANALYSES OF OTHER SPECIAL PURPOSE CAST IRONS

Type or trade name	C %	Si %	Mn %	S %	P %	Ni %	Cr %	Mo %	*Characteristics*
Silal	2.2	5.5	0.6	0.1	0.1	—	—	—	Heat resistant
Pearlitic white cast iron	2.9	1.2	0.8	0.1	0.1	—	—	—	Wear resistant
Ni-hard*	3.0	0.8	0.8	0.1	0.3	4.5	2.1	—	Wear resistant
High chromium cast irons	1.0	0.4	0.4	0.03	0.05	—	30.0	—	Heat and corrosion resistant
	2.7	0.8	0.8	0.03	0.05	—	27.0	—	Wear and corrosion resistant
	3.0	0.8	0.8	0.03	0.05	—	15.0	3.0	Wear and corrosion resistant
Nomag†	3.0	1.5	7.0	0.03	0.05	11	—	—	Non-magnetic
Low expansion cast iron	2.2	1.5	0.8	0.03	0.05	35	2.0	—	Minimum thermal expansion

* Trade name–International Nickel Ltd.
† Trade name–Ferranti Ltd.

CORROSION

Ni-resist, Nicrosilal, high silicon iron and high chromium iron have good corrosion resistance in appropriate media. For example, Ni-resist and Nicrosilal have good resistance to sea water, strong alkalis, inorganic salts and weak acids. These materials are machinable without difficulty. High silicon irons have excellent resistance to sulphuric and nitric acids at all temperatures and concentrations, but have the disadvantage that they are brittle and can only be machined by grinding. High chromium (30%) irons are the only cast irons which can be regarded as stainless so far as atmospheric exposure is concerned. They develop a passive film under oxidizing conditions and their outstanding characteristic is the ability to withstand attack by nitric acid at temperatures up to boiling point and concentrations up to 70%. This grade of iron is machinable without difficulty provided the carbon content is restricted to a maximum of 1.5%.

ABRASION

A graphite-free structure is essential for good resistance to abrasion. The irons which meet this requirement, as shown in Figure 26.7 are the unalloyed pearlitic white irons, martensitic white irons of the Ni-hard type and high carbon high chromium irons.

It is difficult to relate wear characteristics determined in a laboratory to practical service conditions, and there is considerable overlapping between the fields of application for these materials. In the absence of experience of similar conditions, evaluation of material must sometimes be made by trial. In general, martensitic white irons have better abrasion resistance than pearlitic white irons. High chromium, high carbon irons are particularly useful where abrasion is combined with impact loading and where abrasive and corrosive conditions exist together. *See* Chapter 25. Some proprietary special purpose cast irons are listed in Table 26.63.

26.10 Acknowledgements

Valuable assistance in the compilation of data on casting alloys and foundry data from the following organisations.

Steel: SCRATA—Steel Casting Research and Technical Association
Cast Iron: BCIRA—British Cast Iron Research Association
Nickel: INCO—INCO Engineering Products Ltd
Investment Casting: BICTA—British Investment Casters' Technical Association
Magnesium: MEL—Magnesium Electron Ltd
Zinc: ZDA—Zinc Development Association
Copper: CDA—Copper Development Association

27 Engineering ceramics and refractory materials

27.1 Physical and Mechanical Properties of Engineering Ceramics

Intensive development of ceramic materials has increased the availability of well characterized engineering ceramics capable of use over a wide range of temperature (see Tables 27.1 and 27.2).

Table 27.1 SUMMARY OF PROPERTIES OF IMPORTANT ENGINEERING CERAMICS (see also Table 27.2)

Type	*Melting Point* °C	*Density* g/cm³	*Thermal conductivity* W/mK	*Thermal expansion* ($\times 10^6$)	*Young's modulus* GPa	*Strength* MPa	*KIC* MPa
Silicon carbide							
Hot pressed	2200	3.2	20.5	4.55	440	500	3.9
Sintered	—	3.1	—	4.5	395	375	4
Reaction sintered	—	3	—	4.33	360	310	—
Silicon nitride							
Hot pressed	1800d	3.19	25	3.3	300	750	4.8
Sintered	1800d	3.13	—	3.5	245	420	4.8
Reaction bonded	1800d	2.4	8	2.9	175	200	3.6
Sialon	1800d	3.2	19	3	288	800	—
Zirconia							
MgO stabilized	2600	5.75	3.2	9.5	185	6.30	10
Y_2O_3 stabilized	2600	6.1	2.3	10.2	200	1050	8
CeO_2 stabilized	2600	5.7	—	10.7	—	480	15
ZT(A)*(30% ZrO_2)	2050	4.54	—	—	330	770	6
ZT-Mullite (30%)	1850	—	—	—	150	220	2.7

*ZT(A) = zirconia toughened (Alumina).

Table 27.2 PROPERTIES OF PURE CERAMIC MATERIALS*

Material	*Melting point* °C	*Bulk density* g cm^{-3}	*Thermal conductivity* Wm^{-1} K^{-1} *at temp.* °C	*Thermal expansion coefficient* 10^{-6} *to temp.* °C	*Ultimate stress* MPa	*Remarks*
Chromium diboride, CrB_2	2100	5.2	32 at 20	7.5 20	—	Stable in presence of carbon
Hafnium diboride, HfB_2	3250	11.2	6.3 at 20	5.3 500 5.5 1000	—	No reaction with basic slags for 6 minutes at 1520°C. Stable in presence of carbon, no reaction with steel for 6 min at 1620°C

*See also S. J. Burnett, 'Properties of Refractory Materials', UKAEA Research Group, Atomic Energy Research Establishment Harwell, England.

Table 27.2 PROPERTIES OF PURE CERAMIC MATERIALS*—*continued*

Material	*Melting point* °C	*Bulk density* g cm^{-3}	*Thermal conductivity* Wm^{-1}K^{-1} *at temp.* °C	*Thermal expansion coefficient* 10^{-6} *to temp.* °C	*Ultimate stress* MPa	*Remarks*
Tantalum monoboride, TaB	2340	14.0	—	—	—	Oxidation severe at 1100–1400°C. Unstable in presence of carbon
Tantalum diboride, TaB_2	3200	12.4	10.9 at 20 13.9 at 200	—	—	Oxidized in air at 800°C. Stable in presence of carbon
Titanium diboride, TiB_2	2980	4.5	26 at 20 26 at 200	7.6 1000	—	Very stable, even in presence of carbon. Oxidation in air severe at 1100–1400°C. Max. working temperature 2000°C reducing, 800°C oxidizing
Zirconium diboride, ZrB_2	3060	6.1	23 at 20 23–26 at 200	5.5–6.6 1000 7.0 1500	—	No reaction with basic slags at 1520°C for 6 min. No reaction with carbon steel at 1620°C for 2 h. Stable in presence of carbon. Oxidation in air severe at 1100–1400°C. Stable under inert or reducing conditions to over 2000°C
Boron carbide, B_4C	2350	2.51	29 at 20 84 at 425	4.8 500 5.5 1000 6.5 2000 7.1 2500	2900 in compression at 20°C, 155 in compression at 980°C, 300 MOR at 20°C	Attacked by iron, Thermal shock resistance poor. Resistant to air up to 1000°C but max. working temp. 2000°C reducing, 600°C oxidizing
Hafnium monocarbide, HfC	3890	12.2	—	6.3 500 6.25 1000	—	Oxidation in air severe at 1100–1400°C. Stable to 2000°C in He
Silicon carbide, SiC	2700	3.17	42 at 20 21 at 1000	4.6 500 5.5 1500 5.9 2500	550 in compression at 20°C	Quite resistant to oxidation by air up to 1650°C. Thermal shock resistance very good. Reacts with Fe and MgO in basic slags to give silicides. Reacts with iron. High resistance to acid or neutral slags and coal ash: Used in gasifiers, zinc retorts. Also used as abrasive. Used in electrical heating elements. Max. working temp. 2320°C reducing, 1650°C oxidizing (see also table 27.1)

See also S. J. Burnett, 'Properties of Refractory Materials', UKAEA Research Group, Atomic Energy Research Establishment, Harwell, England.

Table 27.2 PROPERTIES OF PURE CERAMIC MATERIALS*—*continued*

Material	*Melting point* °C	*Bulk density* g cm^{-3}	*Thermal conductivity* Wm^{-1}K^{-1} *at temp.* °C	*Thermal expansion coefficient* 10^{-6} *to temp.* °C	*Ultimate stress* MPa	*Remarks*
Tantalum monocarbide, TaC	3 880	14.7	22 at 20	6.3 500 6.7 1 000 8.4 2 500	—	Oxidation in air severe at 1 100–1 400 °C. Useful in He to 3 760 °C
Titanium monocarbide, TiC	3 140	4.25	32 at 20 5.5 at 1 000	7.7 1 000 9.7 2 500	750 to 1 300 in compression at 20 °C	Oxidation in air becomes severe at 1 200 °C. Max useful temp. 3 000 °C in He
Tungsten carbide, WC	2 777	15.7	84 at 20	4.9 1 000 5.8 to 6.1 2 000	—	Oxidation in air severe 500–800 °C useful to 2 000 °C in He. Extremely hard (9 + Mohs. Vickers pyramid 2400) used in drill tips. Max. working temp. 2 000 °C reducing, 550 °C oxidizing
Zirconium monocarbide, ZrC	3 540	6.7	21 at 20	6.1 500 6.6 1 000 7.6 2 000	1 640 at 20 °C compression	Oxidation in air becomes severe at 1 100–1 400 °C. Max. useful temp. 2 350 °C in He
Graphite, C	3 650 (sublimes)	1.50 to 2.25	63 to 210 at 20, parallel to grain. 42 to 130 at 20, perpendicular to grain. 47 at 1 300 34 at 2 500	Parallel: 1 to 4 20 Perpendicular: 2.5 20 to 4.5 4.0 1 000 to 9.8 5.5 1 500 to 11 compression	Parallel 3.5 to 7.6 at 20 °C Perpendicular 3.5 to 70 at 20 °C compression 36 at 2 500 °C compression	Thermal shock resistance very good. Not wetted by iron. Resistant to acidic and basic slags. Oxidized in air above 300 °C. Resistant to non-oxidizing gases. May be 'welded' using molybdenum disilicide. Excellent conductor of electricity
Aluminium nitride, AlN	2 230	3.26	150–180 at 20 °C	4.8 500 5.5 1 000	MOR 300 at 20 °C	Oxidized by O_2 above 1 000 °C. Unstable in water vapour. Stable in N_2–H_2 mixtures at 1 200–1 600 °C
Boron nitride, BN (hexagonal)	2 330 (sublimes)	2.1	15 at 20 27 at 1 000 (Perpendicular values are approx. half of these)	Parallel to pressing direction 2.0 1 000 Perpendicular 13.3 1 000	Parallel to pressing direction 310 at 20 °C Compressive perpendicular 235 at 20 °C compressive	Thermal shock resistance very good when dry. No reaction with iron at 1 600 °C for 30 min. Oxidation in air severe at 1 100–1 400 °C. Stable to 1 000 °C in O_2. Resists attack by molten metals and glasses. Low coeff. of friction. Fabricated by hot pressing. Machines easily. Max. working temp. 2 200 °C reducing, 1 000 °C oxidizing

* *See also* S. J. Burnett, 'Properties of Refractory Materials', UKAEA Research Group, Atomic Energy Research Establishment, Harwell, England.

Table 27.2 PROPERTIES OF PURE CERAMIC MATERIALS*—*continued*

Material	*Melting point* °C	*Bulk density* g cm^{-3}	*Thermal conductivity* Wm^{-1} K^{-1} *at temp.* °C	*Thermal expansion coefficient* 10^{-6} *to temp.* °C	*Ultimate stress* MPa	*Remarks*
Silicon nitride, Si_3N_4	1 900 (sublimes)	3.2	2.3 to 13 at 20 9.4 at 1 200	α phase 2.1 500 3.7 1 500 β phase 1.5 500 3.1 1 500	—	Thermal shock resistance good. Reacts with iron. Useful to 1 850 °C in reducing or inert conditions. Stable in air to 1 200°C. Resistant to molten glasses, molten Al, Pb, Zn, Sn and to HCl, H_2So_4 and HNO_3. Reacts with molten Cu. Slowly attacked by boiling water. May be partially nitrided, machined, then fully nitrided. Used in aluminium handling thermocouple sheaths, cutting tools, wear resistant parts. See Table 27.1
Titanium mononitride, TiN	2 900	5.3	29 at 20 8.5 at 1 000	—	—	No reaction with basic slags. Sightly wetted by carbon steel at 1 620 °C. Poor oxidation resistance to O_2 at 600 °C and to CO_2 at 1 200 °C
Zirconium mononitride, ZrN	2 950	7.1	27 at 20 6.7 at 1 000	6.13 450 7.03 680	—	Slight reaction with cast iron at 1 450 °C for 2 h. Oxidation in air severe at 1 100–1 400 °C. Slow hydrolysis in water
Aluminium oxide, Al_2O_3	2 050	3.97	39 at 20 9.2 at 600 5.9 at 1 400 7.1 at 1 800	7.6 500 8.5 1 000 8.9 to 9.1 1 400	2 940 at 20 °C compressive 48 at 1 600 °C compressive 203 at 20°C shear 23 at 1 500°C shear	Thermal shock resistance fair. Two polymorphic forms, α and γ. α stable above 450 °C (corundum) and γ metastable under all conditions. Good resistance to basic and acidic slags. Max. working temp. 1 900°C (see Table 27.1 for zirconia-toughened alumina)
Beryllium oxide, BeO	2 530	3.00	202 at 100 29 at 1 000 15 at 1 700	7.6 500 8.6 to 9.0 1 000 10.3 1 500 11.1 2 000	786 at 20 °C compressive 48 at 1 600 °C compressive	Becomes volatile at 2 100 °C; very poisonous. Not reduced by carbon or hydrogen. Attacked by acids, fluxed by alumina
Calcium oxide, CaO	2 572	3.32	15.5 at 100 8 at 1 000	11.8 500 13.1 1 000 15.3 1 500	—	Thermal shock resistance fair. Poor resistance to attack by slags containing FeO and SiO_2. Subject to hydration

* *See also* S. J. Burnett, 'Properties of Refractory Materials', UKAEA Research Group, Atomic Energy Research Establishment, Harwell, England.

Table 27.2 PROPERTIES OF PURE CERAMIC MATERIALS*—*continued*

Material	*Melting point* °C	*Bulk density* g cm^{-3}	*Thermal conductivity* Wm^{-1} K^{-1} *at temp.* °C	*Thermal expansion coefficient* 10^{-6} *to temp.* C	*Ultimate stress* MPa	*Remarks*
Cerium dioxide, CeO_2	2600	7.3	—	8.2 500 8.9 1000	—	Useful in air to 2400°C. Not useful in reducing conditions. Subject to hydration
Dichromium trioxide, Cr_2O_3	2435	5.21	—	8.4 500 8.6 1000 8.8 1500	—	Slag resistance good under oxidizing conditions. Less resistant to basic slags
Hafnium dioxide, HfO_2	2810	9.68	—	Monoclinic 5.5 500 5.8 1000 6.4 1700 Tetragonal 1.3 1700 3.0 2000	— —	Useful in air to 2400°C. Stable in H_2 to 1925°C
Magnesium oxide, MgO	2800	3.58	46 at 20 8.4 at 800 6.3 at 1400 9.2 at 1800	12.8 500 13.6 1000 15.1 1500 15.9 1800	83 at 20°C shear 39 at 1300°C shear	Thermal shock resistance poor; can be improved by small amounts of spinel. Resistance to both acidic and basic slags excellent. Limits of usefulness: to 1600°C in vacuum; 1700–1980°C in reducing atmosphere; 2400°C in air. Melts at 2680°C in oxygen-free helium
Silicon dioxide SiO_2	1710	2.32	1.5 at 20 2.5 at 1600	α quartz 22.2 575 β quartz 27.8 575 14.6 1000 Vitreous 0.55 1000		Thermal shock resistance of vitrified silica is excellent Polymorphic forms of silica are quartz, tridymite and cristobalite. The last two of these are metastable under ordinary conditions. Transition temps: quartz-tridymite 870°C. Tridymite-cristobalite 1470°C. Vitreous silica devitrifies at 1100°C
Thorium dioxide ThO_2	3205	9.7	10 to 15 at 20 2.9 at 1000 2.5 at 1400	8.6 500 9.1 1000 to 9.4 1400 10.4	1480 at 20°C compressive 10 at 1500°C compressive 8.3 at 1300°C shear	Thermal shock resistance poor. High resistance to basic slags. Reduced by carbon at high temp. Becomes volatile in He at 2300°C

*See also S. J. Burnett, 'Properties of Refractory Materials', UKAEA Research Group, Atomic Energy Research Establishment, Harwell, England.

Table 27.2 PROPERTIES OF PURE CERAMIC MATERIALS*—*continued*

Material	*Melting point* °C	*Bulk density* g cm^{-3}	*Thermal conductivity* Wm^{-1} K^{-1} *at temp.* °C	*Thermal expansion coefficient* 10^{-6} *to temp.* °C	*Ultimate stress*	*Remarks*
Zirconia, ZrO_2	2690	5.75	2.0 at 25 2.3 at 800 2.7 at 1400	Monoclinic 6.5 500 7.7 1050 Tetragonal 7.9 600 8.3 1400	2070 at 20°C compressive 102 at 20°C compressive 19 at 1500°C compressive	Zirconia phase changes monoclinic → cubic at 1050°C. Thermal shock resistance influenced by volume change accompanying phase change. Stable in oxidizing atmosphere. Fairly stable in reducing atmosphere. Excellent resistance to basic and acidic slags. See Table 27.1 for stabilized zirconia
Mullite, $3Al_2O_3.2SiO_2$	1830	3.15	7.1 at 25 4.0 at 800 3.8 at 1400	5.1 to 5.8 1000°C	16.6 at 1100°C shear	Thermal shock resistance good. Max. working temp. 1650°C (see also Table 27.1)
Magnesia spinel, MgO Al_2O_3	2135	3.51	18 at 25 8 at 600 5.5 at 1200	8.4 1000 to 8.6 9.4 1400	1370 at 550°C compression 59 at 1600°C compression 65 at 20°C shear 37 at 1300°C shear	Resistant to slags containing iron oxide. More resistant than alumina to action of reducing slags. Stable to 1400°C in H_2. Thermal shock resistance fair. Max. working temp. 1950°C
Zircon, $ZrO_2.SiO_2$	2550	4.56	6.1 at 100 4.2 at 800 4.0 at 1400	3.8 500 4.6 1000 5.3 1500	60 at 20°C shear 16 at 1300°C shear	Dissociates above 1700°C. Due to action of slags containing FeO, zircon would dissociate in steel-making environments. Thermal shock resistance good
Molybdenum disilicide, $MoSi_2$	2030	5.95 to 6.24	31.5 at 20 to 200 17 at 1100	7.8 500 8.5 1000 9.0 1500	2280 at 20°C compressive	Carbon reduces melting point to 1870°C. Corrosion in air becomes severe at 1700°C. No attack by O_2 to 1100°C. Used in electrical heating elements
Tungsten disilicide, WSi_2	2165 to 2180	9.25		7.8 500 8.3 1000		Corrosion in air severe above 1950°C

*See also S. J. Burnett, 'Properties of Refractory Materials', UKAEA Research Group, Atomic Energy Research Establishment, Harwell, England.

27.2 Prepared but unshaped refractory materials

Use of these materials is commonly made for installation and/or repair of refractory linings. By definition, unshaped refractory materials are prepared mixtures for use either as delivered or after the addition of an appropriate liquid. This definition covers the refractory cements, mouldable and

Table 27.3 RAW MATERIALS

Raw material	Al_2O_3	CaO	K_2O	Na_2O	MgO	Cr_2O_3	Fe_2O_3	SiO_2	TiO_2	ZrO_2	LOI*	C	S
Andalusite	58.6			5.6		—	—	33.8	—	—	—	—	—
Ball clay (Devon)	20 to 30	0.04	1.2 to 2.7	0.2 to 0.4	0.1 to 0.5	—	0.8 to 1.4	53 to 71	0.9 to 1.6	—	6 to 10	0.1 to 0.7	0.1 to 1.5
Bauxite (Calcined)	84.9	—	0.9	0.9	—	—	3.3	8.0	1.2	—	—	—	—
China clay	38.1	0.1	1.5	0.2	0.2	—	0.7 (FeO)	47.4	—	—	11.9	—	—
Chrome ore (Turkey)	15.0	0.7	—	—	14.0	56.8	12.1	1.5	—	—	—	—	—
Diatomite (Skye)	5.2	1.7	0.1	0.6	1.3	—	3.1	72.1	0.4	—	14.6	—	0.4
Dolomite (Salop)	1.6	31.7	—	—	19.3	—	0.5	1.2	—	—	45.6	—	—
Fireclay	34.9	0.4	1.6		0.9	—	1.9	46.8	1.5	—	11.2	—	—
Flint clay (English)	—	0.3	Trace	0.1	0.2	—	Trace	98.2	—	—	1.4	—	—
Foundry sand (Natural)	8.0	0.1	0.8		0.1	—	0.2	88.4	0.2	—	2.2	—	—
Ganister (Sheffield)	0.9	0.1	—	—	—	—	0.7	96.8	—	—	—	—	—
Kyanite (Kenya)	59.7	0.3	—	—	0.1	—	0.6	37.6	1.1	—	0.6	—	—
Magnesite (Austrian)	0.8	1.8	—	—	88.4	—	6.8	1.4	—	—	—	—	—
Magnesite (Sea water)	0.5	2.2	—	—	93.7	—	1.4	2.1	—	—	—	—	—
Olivine (Norwegian)	0.7	—	—	—	49.0	0.4	6.5	42.0	—	—	1.2	—	—
Quartzite (Welsh)	0.6	0.1	—	—	—	—	0.4 (FeO)	97.8	—	—	—	—	—
Serpentine (Shetland)	2.5	—	—	—	37.6	4.4	6.9	33.2	—	—	15.2	—	—
Silica sand (Pure)	0.5	—	0.1	0.1	—	—	0.1	99.3	—	—	—	—	—
Sillimanite (Australia)	58.8	0.8	0.4	—	0.1	—	2.4	34.5	1.5	—	1.4	—	—
Zircon sand (Australia)	1.2	0.1	—	—	—	0.4	0.4	30.0	2.1	65.4	—	—	—

* Loss on ignition.

castable materials, ramming and gunning mixes. One major difference between materials in this group and brick or blocks is the considerably reduced number of joints in a structure, i.e. these materials tend towards a monolithic construction.

27.3 Aluminous cements

Hydraulic aluminous cement is manufactured by fusing or sintering a mixture of bauxite and limestone. In general the silica content is kept as low as the raw materials permit and it is preferred that the iron should be in the ferric rather than ferrous condition. Commerical aluminous cements vary somewhat in composition but usually lie in the following ranges: SiO_2 4–7%, Al_2O_3 36–42%, Fe_2O_3 8–12%, FeO 4–8%, TiO_2 2–3% and CaO 36–42%. These cements depend on the presence of calcium aluminates for their properties and by adding various forms of alumina, calcined bauxite, chrome and magnesia, it is possible to produce hydraulic cements with excellent refractory properties.

Calcium aluminate cements have unique properties in that they can be moulded, air-hardened and used directly as high-class refractories. They are relatively slow-setting (1–2 h) but rapid-hardening (24 h). In general, the higher the temperature of firing and within limits the higher the percentage of alumina they contain, the more refractory they become. They are notable for their relatively small shrinkage on heating to 400°C and small expansion on heating to 1350°C (0.5–1.5%). Their resistance to heat is very good and the best products can be used up to

Table 27.4 PROPERTIES OF TYPICAL DENSE FIRED REFRACTORY BRICKS

Material	*Chemical analysis* (% by weight)										*Bulk density* g cm^{-3}	*Apparent porosity* %	28 p.s.i. RUL** % *deformation at* °C	*PLC* %††	*Free thermal expansion* %	*Thermal conductivity* $Wm^{-1}K^{-1}$ 500 900 1 300 °C	*Max. service temp.* °C	*Uses*
	Al_2O_3	CaO	Cr_2O_3	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	TiO_2	ZrO_2								
High Alumina†	87	0.3	—	1.5 to 2.0	—	0.2	—	6.6 to 9.5	2.4 to 3.0	—	2.82 to 2.97	17 to 21	10 1 730	0 to −2 2 h 1 600 °C	0.95 to 1 400 °C	1.3 1.6 1.9	1 800	Arc furnace roof torpedo ladle
Fired dolomite	2	55	—	2	—	37	—	3	—	—	2.7	18	—	0 to 0.8 2 h 1 700 °C	1.4 to 1 000 °C	—	—	Rotary kilns
Firebrick†	38	0.5	<0.1	2.9	0.6	0.55	0.5	56	1.4	—	2.1	18 to 25	5 1 500	−0.7 2 h 1 410 °C	0.5 to 1 000 °C	—	—	Ladles, rotary kilns
Chrome–magnesite‡	13 to 16	0.9 to 1.3	17 to 23	9 to 12	—	46 to 52	—	2.5 to 3.5	—	—	2.9 to 3.1	18 to 24	—	0 to +3 5 h 1 700 °C	1.5 to 1 400 °C	1.8 to 2.2	—	Rotary kilns, electric arc furnaces
Firebrick†	41.7	0.5	—	2.7	0.6	0.5	0.1	52.3	1.7	—	1.9 to 2.0	21 to 26	—	0 to −3 2 h 1 600 °C	0.5 to 1 000 °C	1.3 1.5	—	Glass tank furnaces, blast furnace stack
Magnesite–chrome†	10 to 12	0.8 to 1.1	14 to 18	8 to 10	—	60 to 65	—	1.8 to 2.3	—	—	3 to 3.2	16 to 20	—	−0.5 to +3.0 5 h 1 800 °C		2.2 to 2.7	—	Rotary kilns, electric arc furnaces
Magnesite†	0.2 to 0.4	1.8 to 2.3	—	0.15 to 0.3	—	95.5	—	0.7 to 0.9	—	—	2.9 to 3.0	15 to 19	—	−0.2 to −1.5 5 h 1 800 °C	2.1 to 1 400 °C	3.7 to 4.4	—	Electric arc furnaces, LD backing lining
Mullite†	74.2	—	—	0.7	0.7	0.1	0.3	23.2	0.2	—	2.6 to 2.7	13 to 17	2 1 700	−0.2 2 h 1 700 °C	0.63 to 1 400 °C	1.5 1.7 2.0	1 700	Glass tank furnaces

Silica†	0.6	1.7	—	0.5	0.2	0.2	0.2	96.5	0.1	—	1.7 to 1.8	21 to 25	10 1 680	0 4 h 1 600 °C	1.3 to 1 200 °C	1.3 1.7	1 700	Coke ovens, hot blast stoves
Zircon†	1.2	—	—	0.3	—	—	—	31.9	0.3	64.2	3.7 to 3.9	14 to 18	0 1 700	0 2 h 1 600 °C	0.7 to 1 400 °C	2.6 2.4 2.3	1 700	Glass tank furnaces
Carbon‡	—	—	—	—	—	—	—	—	—	—	1.56 to 1.64	—	0 1 700	−0.5 2 h 1 500 °C	0.55 to 1 000 °C	3.6	—	Blast furnace hearth and bosh
Pitch impregnated fired magnesite*	0.15 to 0.25	1.9 to 2.3	—	0.15 to 0.30	—	96.0 to 97.0	—	0.7 to 0.9	—	—	2.85 to 3.0	14 to 18	—	−0.2 to −1.5 5 h 1 800 °C	2.1 to 1 400 °C	3.7 to 4.4	—	LD, Q-BOP

* Data from Steetley Refractories Ltd, Worksop, Notts.
† Data from Pickford Holland Co., Sheffield.
‡ Typical range into which most products fall.

** Refractoriness under load.
†† Permanent linear change.

Table 27.5 PROPERTIES OF TYPICAL UNFIRED REFRACTORY BRICKS

Material	*Chemical analysis* (% by weight)								*Bulk density* g cm^{-3}	*PLC* %**	*Thermal conductivity* Wm^{-1} K^{-1}	*Residual carbon* %	*Loss on ignition* %	*Compressive strength* MPa				*Uses*
	Al_2O_3	CaO	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	TiO_2						20 °C	120 °C	180 °C	300 °C	
Pitch bonded magnesite*	0.5 to 0.7	1.5 to 3.0	0.5 to 1.0	—	92.5 to 96.5	—	0.8 to 1.3	—	2.9 to 3.1	—	3.9 to 4.6 at 900 °C	1.8 to 2.5	3 to 5	—				LD
Chemically bonded high alumina†	86 to 88	0.3	1.5 to 2.0	0.2	0.2	0.2	6.6 to 9.5	2.4 to 3.0	2.9 to 3.1	+1.5 to +3.5 2 h at 1 600 °C	—	—	—	—				Aluminium melting vessels, electric arc furnaces
Pitch bonded dolomite (tempered)*	0.6 to 0.9	53.0 to 57.0	1.8 to 2.4	—	39.0 to 41.0	—	1.0 to 1.6	—	2.80 to 2.95	—	2.4 to 2.9 at 900 °C	1.8 to 2.2	3.8 to 4.8	21 to 42	2 to 6	1 to 6	1 to 4	BOS converters
Pitch bonded magnesia doloma (tempered)*	0.4 to 0.7	21.0 to 26.0	1.0 to 1.5	—	70.0 to 75.0	—	0.8 to 1.2	—	2.87 to 3.02	—	3.5 to 4.1 at 900 °C	2.5 to 3.2	4.2 to 5.2	20 to 40	2 to 6	2 to 6	1 to 4	BOS converters
Pitch bonded magnesia (tempered)*	0.1 to 0.3	1.8 to 2.8	0.2 to 0.5	—	95.0 to 97.0	—	0.7 to 1.0	—	3.00 to 3.15	—	3.8 to 4.4 at 900 °C	3.0 to 3.6	4.5 to 5.5	20 to 40	5 to 20	3 to 14	2 to 6	BOS converters

* Data from Steetley Refractories Ltd, Worksop, Notts.
† Data from Pickford Holland Co., Sheffield.
** Permanent linear change.

Table 27.6 PROPERTIES OF TYPICAL LIGHTWEIGHT FIRED REFRACTORY BRICKS

Material	*Chemical analysis* (% by weight)									*Bulk density* g cm^{-3}	*Apparent porosity* %	*MOR* at room temp.* MPa	*Thermal expansion* %	*Max. service temp.*°C	*Thermal conductivity* Wm^{-1} K^{-1}			*PLC* % at °C	*Uses*
	Al_2O_3	CaO	B_2O_3	Fe_2O_3	K_2O	MgO	Na_2O	SiO_2	TiO_2						400°C	600°C	1 100°C		
Insulating firebrick	38 to 40	1.0 to 14.0	—	0.4 to 2.0	0.1 to 0.3	—	0.1 to 0.3	45 to 55	1.0 to 1.5	0.6 to 0.9	70 to 75	0.8 to 1.0	0.45 to 0.6 to 1000°C	1 300 to 1 400	0.3 to 0.1	0.35 to 0.15	0.4 to 0.25	0 to −1.1 1 300	General insulation
Insulating firebrick	78 to 94	—	—	0.1 to 0.2	0 to 0.1	—	0 to 0.2	—	0 to 0.5	1.2 to 1.4	60 to 65	1 to 3	0.6 to 0.7 to 1000°C	1 700	0.3 to 0.5	0.4 to 0.6	0.4 to 0.6	−0.4 to −0.7 1 700	High temperature insulation
Semi-insulating firebrick	30 to 40	0.2 to 1.6	—	1 to 2	0 to 1	0.1 to 0.6	0 to 1	51 to 61	1 to 2	0.6 to 1.0	—	1 to 3	—	1 320	0.25 to 0.35	0.35 to 0.45	0.45 to 0.55	0 to −0.5 1 300	Rotary kilns
Diatomite insulating brick	—	—	—	—	—	—	—	—	—	0.5 to 0.6	72 to 78	—	—	900	0.15 to 0.17	0.18 to 0.19			Low temperature insulation
											Fibre blanket								
Fibre blanket	47 to 65	0 to 0.2	0 to 1.2	0 to 0.3	0.1 to 0.4	0 to 0.1	0.1 to 0.4	38 to 50	0 to 0.1	—	—	—	—	1 300	0.05 to 0.09	0.09 to 0.22	0.11 to 0.45	−2.5 to −4.0 1 260°C	Low temperature insulation, vacuum degasser gaskets, jointing material, etc.

N.B. Fibre board is similar to fibre blanket but contains a rigidizer. * Modulus of rupture.

1600°C without softening. Calcium aluminate cements lose strength when heated to 400°C, but then remain unchanged up to 1000°C and gradually recover again at higher temperatures.

27.4 Castable materials

These are mixtures of graded refractory aggregate and either a hydraulic cement or a chemical bonding agent. The material is usually supplied dry, and at the appropriate moisture content it may be cast or rammed. Properties of typical materials in this group are shown in Table 27.7. Castable materials are used in monolithic furnace linings, production of special shapes, covers of soaking pits, burner blocks, floors of aluminium holding vessels, cyclones and incinerators.

27.5 Mouldable materials

These are mixtures of graded refractory aggregates and plasticizers, usually clay, supplied mixed with water in a workable condition. Chemical bonding agents may also be incorporated. The workability of the material is such that it may be placed by hand malleting. These materials usually have good thermal shock resistance, but a low compressive strength which does, however, improve after the production of a ceramic bond. The thermal conductivity is usually lower than that of the equivalent fired material.

Mouldables are used in many high temperature vessels, ships' boilers, coke ovens and tunnel kilns.

Properties of a typical material from this group are shown in Table 27.7.

27.6 Ramming material

This is a mixture of graded refractory aggregate with or without the addition of a plasticizer and with or without water usually supplied at a consistency which requires a mechanical method of application. The material is placed in position by means of hand or pneumatic rammers. It is most important that all the material should be compacted to the same extent (i.e. an even density of packing) and that laminations should be avoided.

Ramming mixes are used in copper production vessels, blast furnaces, LD converters, Q–BOP converters, electric arc furnaces, hot metal mixtures, reheat furnaces, soaking pits and spouts of torpedo ladles.

Properties of a phosphate-bonded ramming mix are given in Table 27.7.

27.7 Gunning material

Many of the materials which fall into the above groups may be suitably prepared for application by gunning techniques. The suitably prepared material is introduced into a high pressure compressed air line in a specially designed gun and the material is blasted at the desired area to be lined. Some rebounding of material occurs, but by taking care in preparation and application this may be kept to a minimum.

Material applied by gunning techniques is used for general resurfacing of refractory brickwork, recontouring of ladle linings and installation of flue linings.

27.8 Design of refractory linings

Essential to the designer of refractory structures is a knowledge of the mechanical properties of materials to be used (e.g. thermal expansion, thermal conductivity, Young's modulus and ultimate strength). Standard test methods, such as those described in BS 1902, do not necessarily give the most useful data. The cold crushing strength of a fired brick is generally much greater than its crushing strength at higher temperatures; rectangular blocks heated from one end do not expand as expected from the free thermal expansion; nor is the Young's modulus of a stressed block the same as that of an unstressed block. These last two points are illustrated in Table 27.8.

For these reasons, great care should be taken to ensure that correct expansion allowances and bricking methods are used. Vessels to which this particularly applies are those in which bricks are

Table 27.7 TYPICAL PROPERTIES OF UNSHAPED REFRACTORIES

	Chemical analysis (% by weight)*								*Bulk density* g cm^{-3}			*Max service*	*Thermal conductivity* Wm^{-1} K^{-1}				*MOR*††
Material	Al_2O_3	CaO	Fe_2O_3	MgO	K_2O	Na_2O	SiO_2	TiO_2	Unfired	Fired	*PLC%*** *at* °C	*temp.*°C	400 °C	600 °C	1 100 °C	*Refractoriness*	MPa
Lightweight insulating castable†	30 to 49	9.5 to 12	5 to 8	0 to 1	0 to 1	0 to 1	30 to 50	1 to 2	1.4 to 1.6	1.2 to 1.4	−0.2 to −1.0 1 200 °C	1 300	0.2 to 0.4	0.3 to 0.45		1 350 °C–1 450 °C	—
Dense castable†	96	3	0.1	—	0.05	0.05	0.1	—	2.7 to 3.1	2.6 to 2.9	−1 to +1 1 700 °C	1 800		1.1 to 1.3	1.1 to 2.2	1 800 °C+	—
Ramming mix [Phosphate Bonded]†	83 to 85	0.2	1.6	0.2	0.03	—	9.1 to 10.9	2.7	1.81	—	−1 1 700 °C	1 800	—			1 800 °C+	3.0 at 20°C 14.2 at 1000°C 3.0 at 1400°C
High alumina mouldable†	42 to 70	0 to 10	1 to 5	0 to 0.5	0.2 to 1	0 to 1	25 to 50	0 to 2	—	1.0 to 2.0	−0.5 to +1.5 1 600 °C	1 600		0.35 to 0.6	0.45 to 0.7	—	—

* The chemical constituents of the bonding material are not included: these may include phosphates and organic materials.
** Permanent linear change.
† Data from Pickford Holland Co., Sheffield.
†† Modulus of rupture.

Table 27.8 THERMAL EXPANSION AND YOUNG'S MODULUS FOR FIRED MAGNESITE*

	Temperature °C												
	100	200	300	400	500	600	700	800	900	1 000	1 100	1 200	1 300
Free thermal expansion (%)	0.08	0.24	0.38	0.55	0.70	0.88	1.05	1.21	1.38	1.54	1.71	1.87	—
Thermal expansion measured under thermal gradient heating (%)	0.14	0.29	0.45	0.61	0.76	0.92	1.09	1.25	1.37	1.54	—	—	—
Young's modulus (sonic method) (GPa)	84	83	81	79	78	76	74	73	71	70	69	68	67
Young's modulus measured during restraint of thermal expansion (GPa)	73	28	16	11	9.3	7.8	7.0	6.2	5.0	3.4	1.7	0.81	0.38

* Data published by permission of the British Ceramic Research Association.

suspended, rotated or tilted, e.g. electric arc furnaces, rotary kilns, LD or Q-BOP converters, torpedo ladles or steel ladles.

As a rule of thumb, however, expansion allowances for fired refractories should be approximately half the thermal expansion to the expected temperatures.

In the case of monolithic refractories opinions on expansion allowance vary greatly from no expansion allowance to half the thermal expansion to the expected temperature. With a number of castables there is some evidence to suggest that flexibility of castables in the service environment is sufficient to allow both opinions to be correct.

Expansion allowances may be achieved by placing cardboard, felt, wood or fibre between certain bricks. (N.B. Wood expansion pieces should not be used with silica refractories.)

Table 27.9 INDEX OF REFRACTORY STANDARDS

Subject	*BS*	*DIN*	*ASTM*	*ISO*
Abrasion resistance	1902	—	C704-88	—
Acid resistance	—	—	—	—
Alkali attack		—	C767–86	—
Basic refractories	3056 Part 1	—	—	5417
	3056	—	—	5019
	1902	—	—	—
Bricks — application		1082 Bbl*	—	—
Bricks — dimensions	3056 Part 1	—	C134–34	—
	3056	—	C861–77	—
	3056	—	C861–77	—
	—	—	C909-81	—
	—	—	C134-84	—
Bricks — End arches		1082*	-	1145
— dimensions	--	—	—	—
Bricks — ewtangular - dimensions		—	--	R475
Bricks — side arches -- dimensions	--	1082*		R1145
Bricks - skewbacks — dimensions	—	—	--	
Carbon monoxide attack	1092	—	C288–87	—
Castable refractories	1902	—	C401–84	—
		—	C179–85	—
	—	—	C862–87	—

* Indicates English translation available.

Table 27.9 INDEX OF REFRACTORY STANDARDS—*continued*

Subject	*BS*	*DIN*	*ASTM*	*ISO*
Cement	4550	—	—	—
	—	—	C198–83	—
	—	—	C199–84	—
Chemical analysis — alimina refractories	4140 1902	51077 —	C573–81 —	P803–80 —
Chemical analysis — Aluminosilicate refractories	1902 —	51070 E51083	C573–81 C575–81	— —
Chemical analysis — carbon-containing refractories	—	—	C571–81	—
Chemical analysis — chrome refractories	1902	51074	C572–81	—
Chemical analysis — dolomite	1902	—	C574–84	—
Chemical analysis — magnesia refractories	1902	51073	C574–84	—
Chemical analysis — raw materials	—	—	C572–81	—
Chemical analysis — sample preparation	—	51062*	—	—
Chemical analysis — silicon carbide refractories	— —	51075 51076	— —	— —
Chemical analysis —	—	—	C576–81	—
Chemical analysis —	—	—	C705–84	—
Chemically-bonded basic bricks	—	51050	—	—
Chimneys and flues	4207	1057	—	—
Chrome brick	—	—	C455–84	—
Chrome–Magnesite brick	—	—	C455–84	—
Classification	1902	—	—	1109
Coke ovens	999 4966	1089* —	— —	— —
Cold crushing strength	1902 —	51050 51067	C133–84 C93–84	8895 —
Concrete	1881	1048	C860–83	2736*, 4109, 2
	—	—	C865–87	—
	—	—	C862–87	—
	—	—	C903–88	—
Corrosion resistance	—	V51069	C622–84	—
	—	—	C621–84	—
	—	—	C768–85	—
	—	—	C874–85	—
	—	—	C767–86	—
	—	—	C575–81	—
Creep	—	51053	C832–84	—
Density	— 1902	51050 51057	C914–79 C357–85	— 5018*, 5016
	—	51065	C134–84	—
	—	—	C830–83	—
	—	—	C20–87	—
	—	—	C493–86	—
Drying shrinkage	—	—	C179–85	—
Fireclay products	3056 Part 3	1089	—	5407
	—	51060	C673–84	—
	3056	—	C27–84	—
	—	—	C605–87	—
Glass melting furnaces	4966	—	—	—
	3056 Part 2	—	—	—
Glossary	3446	—	C108–46	836*†
	—	—	C71–85	2246
Grain size	—	51033	—	—
Heat transmission	—	—	C108–46	—
High alumina	3056 Part 3	—	C673–84	5417
	3056	—	C27–84	—
	—	—	C1054–85	—
Hydration	—	—	C492–82	—
	—	—	C544–85	—
	—	—	C620–87	—
	—	—	C456–87	—

* Indicates English translation available.
† Approx. equivalent.

Table 27.9 INDEX OF REFRACTORY STANDARDS—*continued*

Subject	*BS*	*DIN*	*ASTM*	*ISO*
Insulating firebrick	—	—	—	2245
	—	—	C155–84	—
	—	—	C134–84	—
	—	—	C210–85	—
	—	—	C134–84	—
	—	—	C182–88	—
Liquid absorption	—	—	C830–83	—
	—	—	C20–87	—
Magnesite brick	—	—	C455–84	—
Magnesite–chrome brick	—	—	C455–84	—
Modulus of rupture	1902	51048	C133–84	5014, 5013†
	—	—	C583–80	—
	—	—	C607–88	—
	—	—	C93–84	—
Moisture content	—	—	C92–88	—
Monolithic linings	4207	—	—	—
Mullite	—	—	C467–84	—
Non-destructive methods of test	1881	—	—	—
Nozzles, fireclay	—	—	C605–87	—
Pallets	—	—	—	—
Permanent linear change	1902	51066	C113–87	2477
	—	—	—	2478
	—	—	C436–83	—
	—	—	C605–87	—
	—	—	C210–85	—
	—	—	C179–85	—
Permeability	1902	51058	C577–87	—
	—	51050	—	—
Porosity	1902	—	C20–87	5017
	—	—	C830–83	
	—	—	C493–86	—
Pouring pit	—	—	C435–84	—
Pyrometric cone	—	51063	—	R1146
Pyrometric cone equivalent	1902	51063	C24–84	528
Ramming mixes	—	—	C673–84	—
Refractoriness-under-load	1902	51053	—	1893*†
	—	51064	—	—
Rotary cement kilns	3056 Part 3	—	—	5417
Sampling	1902	51061	—	—
	616	—	—	*5022*
Sedimentation	—	51033	—	—
Sieve analysis	1902	51033	C92–88	—
Silica	4966	1089*	C911–87	—
	3056 Part 2	—	C416–84	—
	—	—	C575–81	—
	—	—	C439–61	—
Silicon carbide refractories	—	—	C863–83	—
Slag resistance	—	—	C768–85	—
	—	—	C874–85	—
Specific gravity	1902	—	C830–83	—
	—	—	C20–87	—
	—	—	C604–86	—
	—	—	C135–86	—
Strength testing	1902	—	C67–87	—
	—	—	C16–81	—
Tar-bonded refractories	—	—	C831–88	—
Tar-impregnated refractories	—	—	C831–88	—
Test methods	1902	1089	—	—
	—	V51046	—	—
	—	51048	—	—
Thermocouple reference tables	4937	—	—	—

* Indicates English translation available
† Approx. equivalent

Table 27.9 INDEX OF REFRACTORY STANDARDS–*continued*

Subject	*BS*	*DIN*	*ASTM*	*ISO*
Thermal conductivity	1902	V51046	C201–86	8894
	—	—	C202–86	—
	—	—	C767–86	—
	—	—	C182–88	—
	—	—	C113–89	—
Thermal expansion	1902	51045	C832–84	—
Thermal shock resistance	1902	51068	C38–79	—
	—	E51068	C107–76	—
	—	—	C122–76	—
	—	—	C439–61	—
Unshaped refractory products	1902	51061	C673–84	1927
	—	—	C179–85	—
	—	—	C491–85	—
	—	—	C417–88	—
	—	—	C181–82	—
	—	—	C860–83	—
	—	—	C865–87	—
	—	—	C862–87	—
	—	—	C903–88	—
Warpage	1902	—	—	—
Young's modulus	—	—	C885–87	—
Zircon	—	—	C545–84	—

* Indicates English translation available
† Approx. equivalent

28 Fuels

28.1 Coal

28.1.1 Analysis and testing of coal

SAMPLING FOR ANALYSIS

In order to be representative, the gross sample is compiled by collecting a number of increments spaced evenly throughout the mass of the consignment of coal and, for the specific method, BS1017:Part 1:1977 should be consulted. The mass of an increment is determined by the maximum size of the coal shown in Table 28.1.

Table 28.1 MINIMUM MASS OF INCREMENT AND SIZE OF ENTRY INTO SAMPLING IMPLEMENT

Nominal upper size of coal, mm	< 10	10–25	25–50	50–75	75–100	100–125	125–150	> 150
Minimum size of entry into sampling implement, mm	30	75	150	200	250	320	375	> 375
Minimum mass of increment kg	0.5	1.5	3.0	4.5	6.0	8.0	14.0	> 14

The minimum number of increments required may be obtained from Table 28.2 and is determined by the class of coal and the purpose of the sample. Separate general analysis and total moisture samples may be desirable, e.g. when the coal is very wet, otherwise a common sample can be taken from which both total moisture and general analysis samples are prepared.

Table 28.2 INCREMENTS REQUIRED TO FORM A GROSS SAMPLE

Situation	*Minimum number of increments to be collected from a consignment weighing up to 1000 tonnes*							
	Common sample			*General analysis sample*		*Total moisture sample*		*Size analysis sample*
	Sized coals—dry-cleaned or washed	*Washed smalls (< 50mm)*	*Blended part-treated, untreated, run-of-mine and 'unknown' coals*	*Sized coals—dry-cleaned or washed and unwashed dry coals*	*Blended part-treated, untreated, run-of-mine and 'unknown' coals*	*Sized coals—dry-cleaned or washed and unwashed dry coals*	*Washed smalls (< 50 mm), blended, part-treated, untreated, run-of-mine and 'unknown' coals*	*All coals*
Streams	20	35	35	20	35	20	35	40
Wagons and lorries Barges Sea-going ships (from conveyor during off-loading)	25	35	50	25	50	20	35	40
Sea-going ships (from the hold) Stockpiles	35	35	65	35	65	20	35	40

Reference standards for the precision of measurements on the samples are given in Tables 28.3 and 28.4. The levels of precision represent the 95% probability limits of the deviation of any single value from the true value.

Table 28.3 REFERENCE STANDARDS OF PRECISION FOR MOISTURE AND ASH

True value	*Total moisture*	*Ash (dry basis)*
Below 10%	1% absolute	1% absolute
10% to 20%	0.1 of true value	0.1 of true value
Above 20%	2% absolute	2% absolute

Table 28.4 REFERENCE STANDARDS OF PRECISION FOR SIZE ANALYSIS: PERCENTAGE BETWEEN TWO SIEVES

Per cent in fraction	<5	5–10	10–20	20–30	30–50
Precision % absolute	0.8	1.8	2.7	3.2	3.5

Sampling from a stopped belt is the ideal method for sampling commercial coal and it should be used whenever practicable as the standard against which other methods are checked.

PROXIMATE ANALYSIS Consists of the following determinations (BS 1016: Part 3: 1973):

Total moisture which accounts for the 'free' or adventitious moisture, together with the 'inherent' or original moisture always associated with the coal. Moisture is determined by heating the air-dried coal, ground to pass a 0.2 mm sieve, to 105–110 °C in a vacuum oven or in a stream of nitrogen. The loss in weight is the moisture on the air-dried sample.

Volatile matter is the % loss in weight corrected for moisture when 1 g of the less than 0.2 mm coal is heated in the absence of air to 900 °C.

Ash is determined by placing 1 g of the 0.2 mm coal in a muffle furnace at room temperature, raising the temperature to 500 °C in 30 min, to 815 °C in a further 60–90 min and maintaining this temperature until the residue, which is the ash, is constant in weight.

Fixed carbon is defined as:

100—(moisture + ash + volatile matter)

ULTIMATE ANALYSIS

Requires in addition to ash and moisture determinations (described above) figures for carbon, hydrogen, nitrogen and sulphur.

CALORIFIC VALUE

For practical purposes may be expressed as the number of heat units liberated by the complete combustion of unit weight of coal in a bomb calorimeter. Corrections are made for the formation of nitric and sulphuric acid originally present as nitrogen and sulphur in the coal (BS 1016: Part 5: 1972).

CALCULATION OF CALORIFIC VALUE FROM ULTIMATE ANALYSIS

The calorific value of a fuel may be checked from the ultimate analysis. Usually the calculated value agrees to within 1–2% of the determined value.

In the following formula, which gives the *gross* calorific value (CV), the symbols used give the percentages of: *C*, carbon; *H*, hydrogen; *O*, oxygen; *N*, nitrogen; *S*, sulphur.

Grummell Davies:

$$CV = (0.01522H + 0.937)[C/3 + H - (O - S)/8] \quad MJ\,kg^{-1}$$

Gross and net calorific values All coals contain hydrogen and water, and in the determination of calorific value the water vapour resulting from the combustion of the hydrogen and the vaporization of the original water is condensed to the liquid state. In boiler practice it is not possible to cool the flue gases to a temperature below the dew point and thus the latent heat of condensation of the steam is not recovered.

The *gross* calorific value as determined by the bomb is, therefore, corrected for boiler efficiency work by deducting 2.454 MJ kg^{-1} (1055 Btu lb^{-1}) of water obtained on combustion. The corrected figure is termed the *net* calorific value.

BS SWELLING NUMBER

Provides a means of assessing the tendency of a coal to swell when it is carbonized or used in a combustion appliance. If 1 g of less than 0.2 mm coal is heated in a squat-shaped silica crucible of standard dimensions by a Meker burner (with rich gas) or a Teclu burner with coal gas or a specially designed electric furnace, a coke button of a definite size and shape is produced. By reference to standard profiles a BS swelling number may be assigned to the coal (BS 1016: Part 12: 1959).

ROGA TEST[1]

A mixture of 1 g of less than 0.2 mm coal and 5 g of a standard anthracite is carbonized in a crucible. The resulting coke button is tested in a Roga drum for its resistance to abrasion. From the results obtained the coal coking index (Roga index) is calculated.

GRAY KING COKE TYPE

The caking properties of a coal or blend of coals is assessed by carbonizing in a laboratory assay under standard conditions. The coke residue is classified by comparison with a series of described standard coke types (BS 1016: Part 12: 1959).

AUDIBERT–ARNU DILATOMETER TEST[1]

The test assesses the coking properties of coal or coal blends. A pencil of powdered coal is inserted in a narrow tube and topped by a steel rod which slides in the bore of the tube. The whole is heated at a constant rate. The displacement of the piston is recorded as a function of the temperature. The maximum dilatation and contraction are recorded as a percentage of the original length of the pencil, and the temperatures of the points of softening, maximum dilatation and maximum contraction are noted.

ASH FUSION POINT

Ash fusion point of a coal ash is considered to be a rough guide to its clinkering propensities. The fusion point in a reducing atmosphere is lower by about 40°C than that in an oxidizing atmosphere.

Group 1 Fusion temperature 1425–1710°C, Clinkering troubles absent.
Group 2 Fusion temperature 1200–1425°C. Clinkering manageable.
Group 3 Fusion temperature 1040–1200°C. Clinkering troubles excessive, unless adequate precautions are taken.

The determination is made on a trilateral pyramid, a cube or a right cylinder prepared in a mould from finely ground ash (BS 1016: Part 15: 1970). The test-piece is heated in an oxidizing or a reducing atmosphere defined as follows:

A reducing atmosphere An atmosphere consisting by volume of 50% hydrogen and 50% carbon dioxide with a tolerance of ±5%.

or

An oxidizing atmosphere An atmosphere consisting of either carbon dioxide or air.

The temperatures determined are:

(a) *Deformation temperature.* The temperature at which the first sign of rounding of the tip of the test specimen occurs.

(b) *Hemisphere temperature.* The temperature at which the height of the specimen is equal to half the base, its shape being approximately hemispherical.

(c) *Flow temperature.* The temperature at which the height of the specimen is equal to one third of that at the hemisphere temperature.

CALCULATION OF THE MINERAL MATTER CONTENT OF COAL

All classification systems are based on coal free from mineral matter and moisture. The analytical data for the coal 'as received' thus require correction in the sense of the following equations. The symbols have the following meanings: W_a, moisture; A, ash; V, volatile matter; C, carbon; H, hydrogen; S, sulphur; N, nitrogen; M_b and M_k, estimates of the mineral matter content; all expressed as percentages on the air-dried basis. Q is the calorific value MJ kg^{-1} (Btu lb^{-1}), on air-dried basis and W_t is the total moisture % on the 'as received' or 'as fired' basis.

(a) To convert 'air dried' to 'as received':

$$\text{Multiply } A, V, C, H, S, N, Q \text{ by } \left[\frac{100-W_t}{100-W_a}\right]$$

(b) To convert 'air dried' to 'dry ash-free':

$$\text{Multiply } V, C, H, S, N, Q \text{ by } \left[\frac{100}{100-(W_a+A)}\right]$$

(c) To convert 'air dried' to mineral matter-free basis:

$$\text{Multiply } C, H, N, Q \text{ by } \left[\frac{100}{100-(W_a+M_k)}\right]$$

The volatile matter on a dry mineral matter-free basis is given by[2]

$$\frac{100(V-c)}{[100-(W_a+M_k)]}$$

According to the analysis available the correction c is given by

$$c=0.13A+0.2S_{pyr}+0.7CO_2+0.7Cl-0.20$$

$$\text{or } c=0.13A+0.2S_{total}+0.7CO_2+0.7Cl-0.32$$

$$\text{or } c=0.13A+0.2S_{total}+0.7CO_2-0.12$$

The mineral matter (M_k) is most accurately expressed by a modification of the King, Maries and Crossley[3] formula:

$$M_k=1.13A+0.5S_{pyr}+0.8CO_2-2.8S_{ash}+2.8S_{sulph}+0.5Cl$$

in which A is the determined ash; CO_2, carbon dioxide; S_{pyr}, pyritic sulphur; S_{ash}, sulphur in ash; S_{sulph}, sulphate sulphur in coal; Cl, chlorine.

Where full analytical data are not available the mineral matter (M_b) may be approximately assessed for British coals by the modified BCURA formula:[4]

$$M_b=1.1A+0.53S_{total}+0.74CO_2-0.32\simeq 1.15A$$

28.1.2 Classification

Three major classification systems have been devised based on the proximate analysis of coals.

These are the Fuel Research Board/National Coal Board (NCB) classification,[2] the American ASTM classification,[5] and the International Classification[1] of Hard Coals by Type devised by the Economic Commission for Europe (ECE). The Fuel Research Board/NCB classification is described below and outlines are given of the others. The technological characteristics of coals are better defined in terms of their petrographical constituents and a coal classification system on this basis is in prospect.

FUEL RESEARCH BOARD/NCB CLASSIFICATION[2]

Coals are assigned code numbers according to their volatile matter content on a dry, mineral matter-free basis and their caking propensities are assessed by the Gray–King low temperature assay (BS 1016: Part 12: 1959). Clean coal must be used for determining the Gray–King coke type, and if the coal has initially a higher ash content than 10% it is floated at such a specific gravity as will give the maximum yield of coal with not more than 10% of ash.

Using the criterion of volatile matter alone, a first division into the following groups is obtained:

	Volatile matter	*Code no.*
Anthracites	Under 9.1%	100
Low-volatile steam coals	9.1–19.5%	200
Medium-volatile coals	19.6–32.0%	300
High-volatile coals	Over 32%	*See* Table 28.5

In the first three groups, i.e in coals of volatile matter up to 32%, there is a close relationship between volatile matter content and caking properties. Consequently, the effect of subdividing into progressive ranges of volatile matter content is also to produce classes with progressive ranges of caking power. The corresponding Gray–King coke types are given in Table 28.5 as an indication of caking properties.

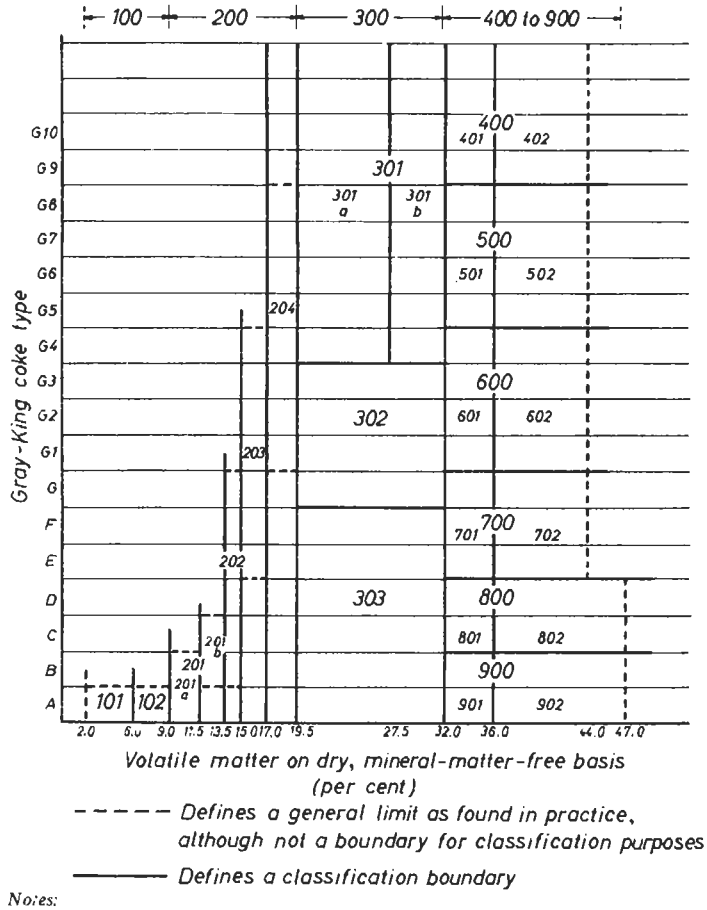
In the fourth group, i.e. in coals with more than 32% of volatile matter—there is a wide range of caking properties at any given volatile matter content, and subdivision has been made on the basis of the Gray–King coke type. Six ranges of caking properties, listed in Table 28.5, are recognized for these high-volatile coals.

Each of the 400–900 classes can be further subdivided according to volatile-matter content: a 1 in the third figure of the code number indicates that the volatile matter lies between 32.1 and 36.0, and a 2 that it is over 36%. Also, a subdivision is made of the 301 class into 301a and 301b with volatile ranges of 19.6–27.5% and 27.6–32% respectively.

Certain coals have been affected by the heat from nearby igneous intrusions, with the result that their caking properties are generally subnormal compared with those of other coals of similar volatile content. These affected coals are distinguished by the code numbers 201H, 203H, 302H and 303H. They occur mainly in Scotland, but some are found in Durham.

A full list of code numbers, with ranges of volatile contents and caking properties, is given in Table 28.5.

Table 28.5 COAL CLASSIFICATION SYSTEM USED BY NATIONAL COAL BOARD (REVISION OF 1964)



Notes:

(1) Coals that have been affected by igneous intrusions ('heat-altered' coals) occur mainly in classes 100, 200 and 300, and when recognized should be distinguished by adding the suffix H to the coal rank code, e.g. 102H, 201bH.

(2) Coals that have been oxidized by weathering may occur in any class, and when recognized should be distinguished by adding the suffix W to the coal rank code, e.g. 801W.

ASTM CLASSIFICATION OF COALS BY RANK[5]

Coals are classified according to their fixed carbon and calorific value expressed in Btu lb^{-1} on a mineral matter-free basis. The higher rank coals are classified according to fixed carbon on the dry basis; the lower rank coals are classified according to calorific value on the moist basis. Agglomerating character is used to differentiate between certain adjacent groups. There are four classes: I anthracite, II bituminous, III sub-bituminous, IV lignite, each containing a number of named groups. The position of a coal in the scale of rank can be expressed in a condensed form, e.g. (62–146) in which the parentheses signify that the contained numbers are on a mineral matter-free basis. The first number represents the fixed carbon on the dry basis reported to the nearest whole per cent, the second the calorific value expressed as hundreds of Btu lb^{-1} to the nearest hundred.

ECE INTERNATIONAL CLASSIFICATION OF HARD COALS[1]

Coals are first placed in classes according to their volatile matter on the dry ash free basis. Then

coals with a volatile matter greater than 33% are placed in classes according to their gross calorific value, Table 28.6.

Table 28.6 DIVISION OF COALS INTO CLASSES (ECE)

Class number	*Volatile matter* % d.a.f.	*Class number*	*Gross calorific value moist ash free* kcal kg^{-1} (MJ kg^{-1})
1A	3–6.5	6	>7 750 (32.5)
1B	>6.5–10	7	>7 200–7 750 (30.1–32.5)
2	>10–14	8	>6 100–7 200 (25.5–30.1)
3	>14–20	9	>5 700–6 100 (23.9–25.5)
4	>20–28		
5	>28–33		
6–9	>33		

Each class is further subdivided into groups according to their caking properties expressed either by their crucible swelling number or their Roga index, Table 28.7.

Table 28.7 DIVISION OF COAL CLASSES INTO GROUPS (ECE)

Group number	*Crucible swelling number*	*Roga index*
1	0–½	0–5
2	1–2	5–20
3	2½–4	20–45
4	>4	>45

Each group is then subdivided into subgroups according to their coking properties assessed by their maximum dilatation in the Audibert–Arnu dilatometer test or by their Gray–King coke type, Table 28.8.

Table 28.8 DIVISION OF COAL GROUPS INTO SUBGROUPS (ECE)

Subgroup number	*Maximum dilatation*	*Gray–King coke type*
0	Non-softening	A
1	Contraction only	B–D
2	0 and less	E–G
3	>0–50	G1–G4
4	>50–140	G5–G8
5	>140	>G8

A three-digit code number is used to describe the classified coal. The first digit indicates the class, the second digit the group, and the third digit the subgroup.

28.1.3 Physical properties of coal

Table 28.9 PHYSICAL PROPERTIES OF COAL

	Density $kg\,m^{-3}$	*Bulk density* $kg\,m^{-3}$ ($lb\,ft^{-3}$)	*Specific heat* $kJ\,kg^{-1}\,K^{-1}$	*Coeff. linear thermal exp.*‡ $10^{-6}\,K^{-1}$ 30°C	90°C	220°C	330°C
Fusain	—	—	0.88–0.92	—	—	—	—
Bituminous coal	1 250–1 450	600–670 (38–42)	1.00–1.09	33	—	45	60
Anthracite	1 400–1 700	700–790 (44–49)	0.92–0.96	—	—	—	—
Anthracite parallel to bedding plane	—	—	—	—	15	16.5	18
Anthracite perp. to bedding plane	—	—	—	—	27	29	29
Coal ash	—	—	0.67–0.71	—	—	—	—

* The approximate bulk densities refer to dry graded coals loosely packed in large containers. The bulk density is influenced by: (1) size and grading; (2) size of the container; (3) % 'free' moisture in excess of the inherent moisture; (4) shape of particles; (5) method of packing.
† Reference 6. The specific heat of coal increases with increase in volatile content and decrease in the carbon/hydrogen ratio.
‡ Data supplied by British Coal Utilization Research Association.

Methods for predicting the specific heat, enthalpy, and entropy of coal, char, tar and ash as a function of temperature and material composition are presented in reference 7.

The mean thermal conductivity, k, of coking coals between 0°C and t°C is given approximately by

$$k = 130 + 0.67t + 0.00067t^2 \quad mW\ m^{-1}K^{-1}$$

28.2 Metallurgical cokes

28.2.1 Analysis and testing of coke

SAMPLING FOR ANALYSIS AND SHATTER TEST

Analysis In order to obtain a representative sample cokes are divided into four classes as follows:

Class 1: Large or graded gas coke from which breeze has been removed.
Class 2: Large or graded oven cokes from which breeze has been removed.
Class 3: Gas or oven cokes from which breeze has not been removed.
Class 4: Breeze.

In order to obtain a specified accuracy for any particular determination the number of increments required depends on the type of coke, its moisture, the degree of accuracy chosen and, in many cases, the conditions under which the sampling is to be carried out. The number of increments is independent of the total weight of coke sampled.

Table 28.10 TYPICAL ANALYSES OF SOLID FUELS

The table attempts to give analyses for fuels falling into each of the classes given but it should be understood that they can only be considered as a guide and that wide variations will be encountered among fuels belonging to each class

	Anthracite	*Semi-anthracite*	*Semi-bituminous coals*	*Bituminous coals*							*Lignite*	*Peat*	*Wood*	*Manufactured fuels*		
														Charcoal	*Coke*	*Semi-coke*
Code numbers: NCB	100a	201	204	301a	401	502	601	702	802	902	—	—	—	—	—	—
ECE	120A	221	344	445	545	844	843	832	821	921	—	—	—	—	—	—
Proximate analysis (air-dried basis)																
Moisture	1.0	1.0	1.0	0.9	0.9	1.9	2.0	5.8	8.6	13.8	15.0	20.0	15.0	2.0	2.5	2.5
Volatile matter less moisture	5.0	11.2	17.9	25.9	30.8	34.4	32.7	33.6	34.0	34.7	40.0	50.0	70.0	8.0	1.5	8.5
Fixed carbon	91.0	83.8	77.1	71.3	64.0	56.6	58.5	55.3	52.5	46.9	40.0	25.0	14.5	89.0	88.0	80.0
Ash	3.0	4.0	4.0	1.9	4.3	7.1	6.8	5.3	4.9	4.6	5.0	0.5	0.5	1.0	8.0	9.0
Volatile matter (dry, ash-free)	5.2	11.8	18.8	26.6	32.3	37.8	35.9	37.8	39.4	42.5	50.0	66.7	82.8	8.2	1.7	9.6
Ultimate analysis (air-dried coal)																
Carbon	89.4	86.9	86.0	86.6	83.5	76.7	77.0	74.4	70.0	64.6	55.2	43.1	42.4	90.4	85.1	82.3
Hydrogen	2.9	3.8	4.3	4.8	5.1	4.9	4.8	4.8	4.6	4.4	3.9	4.6	5.1	2.4	0.8	2.7
Nitrogen	1.1	1.2	1.3	1.6	1.5	1.6	1.5	1.5	1.2	1.3	0.7	0.6	0.3	0.8	0.9	0.9
Sulphur	0.9	1.0	1.0	0.8	1.1	2.6	1.5	1.1	0.9	0.6	0.6	1.3	0.3	0.7	0.7	1.1
Oxygen and errors	1.7	2.1	2.4	3.4	3.6	5.2	6.4	7.1	9.8	10.7	19.6	25.4	36.4	2.7	1.6	1.5
*Ultimate analysis (dry, mineral water-free basis)**																
Carbon	93.5	92.0	91.0	89.4	88.8	85.9	85.6	84.3	81.7	79.9	69.0	57.5	50.2	93.2	95.1	93.0
Hydrogen	3.0	4.0	4.5	5.0	5.3	5.4	5.3	5.3	5.4	5.4	4.9	6.1	6.0	2.5	0.9	3.1
Nitrogen	1.2	1.3	1.4	1.7	1.6	1.7	1.7	1.7	1.4	1.6	0.9	0.8	0.4	0.8	1.0	1.0
Sulphur†	0.9	1.1	1.1	0.8	0.8	1.2	1.2	0.8	1.1	0.8	0.7	1.8	0.4	0.7	1.2	1.2
Oxygen and errors	1.4	1.6	2.0	3.1	3.5	5.8	6.2	7.9	10.4	12.3	24.5	33.8	43.0	2.8	1.8	1.7
Caking and swelling tests																
BS swelling number	1	2	7	8	9	8	7	3½	1½	1	—	—	—	—	—	—
Gray-King coke type	A	B	G6	G9	G10	G6	G4	E	C	B	—	—	—	—	—	—
Calorific value MJ kg^{-1} (Btu lb^{-1})																
Air-dried coal	34.24 (14 720)	34.52 (14 840)	34.61 (14 880)	35.00 (15 050)	34.35 (14 770)	31.91 (13 720)	31.82 (13 680)	30.42 (13 080)	28.28 (12 160)	26.05 (11 200)	21.03 (9 040)	16.68 (7 170)	15.75 (6 770)	33.70 (14 500)	30.17 (12 970)	30.38 (13 060)
Dry, mineral matter-free coal	35.80 (15 400)	36.52 (15 700)	36.63 (15 750)	36.66 (15 760)	36.52 (15 700)	35.59 (15 300)	35.54 (15 280)	34.42 (14 800)	33.00 (14 190)	32.19 (13 840)	26.30 (11 300)	22.24 (9 560)	18.60 (8 010)	34.77 (14 950)	33.70 (14 490)	34.33 (14 760)

* Dry, ash-free basis for lignite, peat, wood and manufactured fuels.
† Organic sulphur for coals.

The number of increments of the various classes of coke for ash and moisture determinations required to give an accuracy of ±1% at the 95% probability level is given in Table 28.11 and the weight of the increments in Table 28.12 according to BS 1017: Part 2: 1960.

Table 28.11 NUMBER OF INCREMENTS FOR ACCURACY OF ±1%

Class	*Moisture*		
	3% or less	*3–5%*	*Over 5%*
1	32	32	48
2	48	72	108
3	100	150	225
4	16	16	16

Table 28.12 WEIGHT OF INCREMENT AND SAMPLING IMPLEMENTS

Maximum size of coke	*Sampling implement*
38 mm (1½ in) (i.e. not more than 5% over 1½ in)	1.14 kg (2½ lb) scoop
76 mm (3 in) (i.e. not more than 5% over 3 in)	2.3 kg (5 lb) scoop
101 mm (4 in) (i.e. not more than 5% over 4 in)	4.5 kg (10 lb) scoop
Over 101 mm (4 in)	6.8 kg (15 lb) scoop

Shatter test According to BS 1016: Part 13: 1969 the gross sample of 25 kg for the shatter test should be collected specifically for the test according to BS 1017: Part 2: 1960 and should contain all the sizes over 51 mm (2 in) in approximately the same proportion as are found in the original size analysis.

GENERAL

The qualities of coke which have the most influence on metallurgical practice are purity, hardness and combustibility. The purity of any particular sample is determined by chemical tests, but the physical properties of hardness and combustibility may only be assessed by empirical tests.[8]

CHEMICAL ANALYSIS

Chemical analysis normally includes determinations of water, ash, volatile matter and sulphur. Phosphorus is important in the manufacture of acid pig iron.

The carbon content of a coke is an index of its thermal value and is roughly assessed by subtracting the 'impurities', as determined by chemical analysis, from 100.

OTHER TESTS

The size of coke is specified by the size of the square meshed screen through which it passes or on which it rests, the results being expressed as cumulative percentages on screens of decreasing sizes.

Bulk density of coke This is an indication of the weight of the lump material that will fill a known (large) volume. The cubical container used has a capacity of 0.1 m^3 (2 ft^3), 465 mm (15 in) side internally (BS 1016: Part 13: 1969).

Apparent specific gravity is the ratio of the weight of a given volume of coke to the weight of an equal volume of water (BS 1016: Part 13: 1969).

True specific gravity is the ratio of the weight of a given volume of dry coke passing a 0.2 mm test sieve to the weight of an equal volume of water at the same (atmospheric) temperature (BS 1016: Part 13: 1969).

Porosity may be either 'apparent' or 'total'.

$$\% \text{ apparent porosity} = \left[\frac{\text{volume of open pores}}{\text{volume of coke}}\right] \times 100$$

$$= \left[\frac{W_3 - W_1}{W_3 - W_2}\right] \times 100$$

where W_1 = weight of dried coke, W_2 = weight of coke saturated with water weighed in a tank of cold water, W_3 = weight of coke saturated with water.

It can also be shown that:

$$\% \text{ total porosity} = \left[\frac{\text{real specific gravity} - \text{apparent specific gravity}}{\text{real specific gravity}}\right] \times 100$$

The real specific gravity in the above expression is determined by the specific gravity bottle method on material passing a 0.2 mm sieve, care being taken, however, to boil the coke with water in order to remove air and to saturate it (BS 1016:Part 13:1969).

The apparent specific gravity may be obtained from weighings required by the apparent porosity:

$$\text{apparent specific gravity} = \frac{W_1}{W_3 - W_2}$$

The micum indices of a coke should measure its liability to attrition in the blast furnace. It is determined as follows: 25 kg of coke over 60 mm in size and with less than 5% moisture is placed in a special drum and rotated for 100 revolutions. A size analysis of the coke is then made and the percentages of coke remaining on a 40 mm sieve (M_{40}) and passing through a 10 mm sieve (M_{10}) are normally reported (BS 1016:Part 13:1969).

The 'shatter index' is a measure of the liability of a coke to form breeze during loading, unloading and charging operations.

To determine this index 25 kg of greater than 51 mm (2 in) coke is dropped four times from a special box which is placed 1.83 m (6 ft) above a cast iron or steel plate. The shattered coke is then screened and the average of three tests of the percentages retained on 51 mm (2 in), 38 mm ($1\frac{1}{2}$ in), 25 mm (1 in) and 13 mm ($\frac{1}{2}$ in) square aperture screens are reported as respective shatter indices (BS 1016:Part 13:1969).

The reactivity of coke determines its behaviour towards air or oxygen or the rate with which it reduces carbon dioxide to monoxide.

The 'critical air blast' (CAB), determines the reactivity of coke to air by finding, by trial and error, the minimum rate of blast which will maintain combustion in an ignited bed of 1.2–0.6 mm coke contained in a glass or quartz tube of specified dimensions (BS 1016: Part 13: 1969).

The thermal value of the volatile matter remaining in the coke (volatile therms) is a measure of its ignitability and, indirectly, of its reactivity to air (BS 1016:Part 13:1969).

28.2.2 Properties of metallurgical coke

BLAST FURNACE COKE

A specification for blast furnace coke proposed by the BSC/BISRA iron-making panel of the Iron and Steel Institute (Publication P127:1969) is shown in Table 28.13.

Table 28.13 SPECIFICATION FOR BLAST-FURNACE COKE

Moisture content
This shall not exceed 3%; a mean of 2% is desired
Variation −2 to +3 on single samples
−0.3 to +0.5 on weekly average

Size
The overall size range shall be 19–64 mm ($\frac{3}{4}$–2$\frac{1}{2}$ in); this implies pre-crushing of the coke

Shatter index
The 38 mm (1$\frac{1}{2}$ in) shatter index shall not be less than 90
Variation ±2 on single samples
±0.3 on weekly average

Micum index
The M_{40} index shall not be less than 75
Variation ±3 on single samples
±0.45 on weekly average

The M_{10} index shall not exceed 7
Variation ±1 on single samples
±0.45 on weekly average

Ash content
The ash content should not exceed 3%
Variation ±1.7 on single samples
±0.27 on weekly average

Sulphur content
The sulphur content should not exceed 0.6%
Variation ±0.17 on single samples
±0.03 on weekly average

A size range of 20–80 mm as charged and with higher ash is more usual. Consistency of the properties of the coke supplied is of the utmost importance.

Table 28.14 PROPERTIES OF COKES

Real density, kg m^{-3}	1 700–2 000
Apparent density, kg m^{-3}	700–1 100
Total porosity, %	36–55
Apparent porosity, %	35–47
Calorific value, MJ kg^{-1}	33.14
Ash, % dry	8–11
Volatile matter	0.6–1.1
Sulphur	0.57–1.4
Phosphorus	0.01–0.14
Critical air blast, l min^{-1}	1.56–2.4

FOUNDRY COKE

The range of properties specified[9] for foundry coke from various plants in Wales and Durham is given in Table 28.15. These supersede the recommendations of TS 47 1959[10].

Table 28.15 SPECIFICATION FOR FOUNDRY COKE

Moisture, % maximum	3.0–5.5
Ash, % maximum	9
Volatile matter, % maximum	0.7–1.0
Sulphur, % maximum	0.85–1.0
Shatter index, 50 mm (2 in) minimum	90
Mean size minimum, mm	102–107
(in)	(4–4.2)
Undersize, not more than 4% less than 50 mm (2 in)	

There are indications[11] that a narrow range of size of coke as charged is more important to the operation of the cupola furnace than the mean size in the size range 40–110 mm and that there is little to be gained by using large coke. Consistency in the properties of the coke supplied is most important.

FORMED COKE

Processes developed to produce formed coke briquettes[12] from weakly coking coals are shown in Table 28.16. Properties of formed cokes used in blast furnace trials are given in Table 28.17.

Table 28.16 CHARACTERISTICS OF FORMED COKE PROCESSES

Process	*Forming*	*Feed*	*Binder*
BBF	Hot briquetting	Any coal	30% caking coal
Consol–BNR	Hot pelletizing	High-volatile coal	Caking coal
Iniex	Briquetting	Low-volatile, non-caking	Pitch
FMC	Briquetting	High-volatile coal	Pitch
Sapoznikov	Hot briquetting	Slightly caking	Caking coal
Guiprokoks	Hot briquetting	Low–medium volatile, weakly caking	High-volatile, weakly caking coal
DKS	Briquetting	Non-caking	Pitch and caking coal

Table 28.17 PROPERTIES OF FORMED COKE BRIQUETTES

	Process and coal source				
Property	*BBF,* Germany*	*BBF,* UK*	*FMC, USA*	*DKS Japan*	*GI, USSR*
Analysis, dry %					
Fixed carbon	81.5	81.2	89.9	80.3	na
Ash	5.5	12.1	5.5	12.6	na
Volatile matter	9.1	6.0	3.9	6.5	1.5
Sulphur	0.9	1.0	0.7	0.5	na
Bulk density, kg m^{-3}	578	622	554	779	na
Strength					
M+40	84	86	—	—	85–90
M+30	—	—	95	—	—
M+20	—	—	—	94	—
M−10	9.3	10.9	5.1	5.6	7–8

* Non-calcined.
na—not available.

BULK DENSITY OF COKE

A graded coke 20–40 mm with normal ash and moisture has a bulk density of 420–480 kg m^{-3}, and run of oven coke 460–510 kg m^{-3}.

SPECIFIC HEAT OF COKE[13]

The relationship between the specific heat of coke and the ash content is a linear one. Values for the mean specific heat between 21° and t °C are given in Table 21.18, where A denotes % ash present in the coke.

Table 28.18 MEAN SPECIFIC HEAT OF COKE

Temperature °C	*Mean specific heat* kJ kg^{-1} K^{-1}
400	1.11–0.001 8 A
500	1.26–0.002 8 A
600	1.36–0.003 4 A
700	1.45–0.004 4 A
800	1.50–0.004 5 A
900	1.56–0.005 4 A
1 000	1.60–0.005 7 A
1 100	1.63–0.005 7 A
1 200	1.66–0.005 7 A
1 300	1.69–0.005 7 A

Table 28.19 THERMAL EXPANSION OF COKE*

Temperature of measurement °C	*Coefficient of linear thermal expansion* 10^{-6} K^{-1}			
	Bituminous coal. Strongly coking Carbonization temp. °C		*Bituminous coal. Weakly coking Carbonization temp.* °C	
	600	1000	600	1000
100	9.0	3.4	6.8	1.8
200	10.0	4.1	7.8	1.8
300	10.5	4.5	8.0	2.3
400	—	4.6	8.0	—

* Data provided by BCURA.

28.3 Gaseous fuels, liquid fuels and energy requirements

28.3.1 Liquid fuels

Liquid fuels are easy to handle, store and control. The two main groups are derived from (1) petroleum, (2) coal carbonization. (In the long term we must expect a full range of liquid fuels manufactured from coal either by gasification and synthesis or by direct routes involving pyrolyses, solvent extraction and hydrogenation.) Distillate fuels contain practically no ash, and residual fuels contain very little ash in comparison with solid fuels. Sulphur in residual fuel oil depends mainly on the source of the crude oil from which it was obtained. High sulphur contents are usually undesirable metallurgically. Slagging troubles occur at over 700 °C owing to the presence of Na_2O, S and V_2O_5 in the fuel. The higher flame emissivity of coal tar fuels is an advantage in high temperature processes.[14]

British Standards specifications[15, 16] for liquid fuels are intended as a guide but more details should be specified for metallurgical use of fuel. Tables 28.20 and 28.21 refer to typical properties of petroleum and tar fuels respectively.

Table 28.20 PETROLEUM LIQUID FUELS

	Kinematic viscosity cSt (10^{-2} m^2 s^{-1})	*I.B.P.* °C	*F.B.P.* °C	*Specific gravity* 15.6°/ 15.6 °C 60°/ 60 °F	C %	H %	O+N %	S %	*Ash* %	*Calorific value* MJ kg^{-1} (Btu lb^{-1}) *gross*
	at 37.8 °C (100 °F)									
Primary flash distillate	—	37	72	0.649	83.98	16.0	—	0.02	—	47.9 (20 600)
Primary flash distillate	—	32	163	0.704	84.87	15.0	—	0.03	—	47.1 (20 250)
Kerosine	1–2	160	185	0.78	85.9	14.0	—	0.08	—	46.5 (20 000)
Gas oil	3.3	190	—	0.844	85.3	13.2	—	0.30	0.001	45.4 (19 600)
Gas oil	3.3	190	—	0.833	85.0	13.05	—	0.95	0.001	45.6 (19 500)
	at 82.2 °C (180 °F)									
Light fuel oil	10	—	H_2O%	0.935	85.55	11.50	0.70	2.55	0.02	43.3 (18 600)
Light fuel oil	12.5	—	—	0.99	86.94	11.4	0.5	1.1	0.06	42.9 (18 450)
Medium fuel oil	30	—	0.05	0.967	84.12	11.50	0.8	3.5	0.03	42.6 (18 300)
Medium fuel oil	34	—	0.05	0.968	85.85	11.83	0.8	1.4	0.03	42.98 (18 480)
Heavy fuel oil	50	—	0.1	0.950	85.2	11.70	1.0	1.9	0.1	43.0 (18 500)
Heavy fuel oil	70	—	0.1	0.980	84.5	10.7	0.8	3.8	0.1	42.6 (18 300)
Heavy fuel oil	72	—	0.25	0.939	87.6	11.07	0.9	0.36	0.02	43.7 (18 780)

Table 28.21 COAL TAR FUELS

Type	*CTF* 50	*CTF* 100	*CTF* 200	*CTF* 250	*CTF* 300	*CTF* 400	*Hard pitch*	*Crude tar*
Specific gravity	1.010	1.025	1.145	1.175	1.205	1.245	1.22	1.165
Calorific value, gross								
MJ kg^{-1}	39.66	39.43	38.77	38.59	38.49	37.63	37.22	37.68
(Btu lb^{-1})	(17 050)	(16 950)	(16 670)	(16 590)	(16 550)	(16 180)	(16 000)	(16 200)
Calorific value, net								
MJ kg^{-1}	38.03	37.91	37.45	37.29	37.24	36.49	36.15	36.49
(Btu lb^{-1})	(16 350)	(16 300)	(16 100)	(16 030)	(16 010)	(15 690)	(15 540)	(15 690)
Viscosity								
cSt (10^{-2} m^2 s^{-1})	13	24	300	35 000	25 000	—	—	~300
at temp °C	37.8	37.8	37.8	30	55			37.8
Analysis, %								
C	87.65	88.80	89.36	89.57	89.88	90.42	90.66	90.5
H	7.38	6.90	5.90	5.90	5.73	5.23	4.90	5.4
O (difference)	3.35	2.79	2.49	2.33	2.23	2.01	1.70	1.7
N	0.92	0.84	1.11	1.16	1.22	1.38	1.42	1.13
S	0.66	0.63	0.89	0.84	0.69	0.65	0.86	0.6
Ash	0.04	0.04	0.10	0.20	0.25	0.31	0.46	0.5

(A) CALORIFIC VALUE

In the absence of a bomb calorimeter determination, approximate values may be calculated for petroleum oils, or tars. However, the correlations are separate for each group.

gross calorific value $= 51.91 - 8.79d^2 - \{0.5191 - 0.0879d^2(\%H_2O + \%\text{ ash} + \%S)\} + 0.0942(\%S)$ MJ kg^{-1}

or $22.320 - 3780d^2 - \{223 - 37.8d^2(\%H_2O + \%\text{ ash} + \%S)\} + 40.5(\%S)$ Btu lb^{-1}

$\doteq 59.91 - 8.79d^2$ MJ kg^{-1}

or $22\,320 - 3780d^2$ Btu lb^{-1} (reference 17)

net calorific value $= 46.5 + 3.14d - 8.84d^2$ MJ kg^{-1}

or $20\,000 + 1350d - 3800d^2$ Btu lb^{-1} (reference 17)

where d is the specific gravity (relative density) at 15.6 °C (60 °F) for petroleum oils.

The net calorific values are about 2.8 MJ kg^{-1} (1200 Btu lb^{-1}) less than the gross values for distillate fuels down to about 2.3 MJ kg^{-1} (1000 Btu lb^{-1}), less for heavy fuel oils.

For tar fuels:

gross calorific value $= 0.337(\%\text{ C}) + 1.44(\%\text{ H} - \frac{1}{8}\%\text{ O}) + 0.093(\%\text{ S})$ MJ kg^{-1}

or $145(\%\text{ C}) + 620(\%\text{ H} - \frac{1}{8}\%\text{ O}) + 40(\%\text{ S})$ Btu lb^{-1} (reference 18)

net calorific value $= 0.75$ (gross CV $+ 10.9$) MJ kg^{-1}

or 0.75 (gross CV + 4700) Btu lb^{-1} (reference 18)

(B) SPECIFIC GRAVITY CORRECTION COEFFICIENTS PER 1 °C

Table 28.22 CORRECTION COEFFICIENTS FOR PETROLEUM PRODUCTS[19]

Specific gravity 15.6/15.6 °C (60/60 °F)	*Correction coeff. per* 1 °C	*Specific gravity* 15.6/15.6 °C (60/60 °F)	*Correction coeff. per* 1 °C
0.605 0–0.613 3	0.001	0.742 5–0.753 7	0.000 79
0.613 4–0.621 9	0.000 99	0.753 8–0.764 9	0.000 77
0.622 0–0.632 0	0.000 97	0.765 0–0.776 0	0.000 76
0.632 1–0.641 9	0.000 95	0.776 1–0.786 9	0.000 74
0.642 0–0.653 0	0.000 94	0.787 0–0.798 8	0.000 72
0.653 1–0.664 9	0.000 92	0.798 9–0.812 4	0.000 70
0.665 0–0.677 5	0.000 90	0.812 5–0.828 3	0.000 68
0.677 6–0.689 9	0.000 88	0.828 4–0.859 9	0.000 67
0.690 0–0.702 5	0.000 86	0.860 0–0.925 0	0.000 65
0.702 6–0.716 6	0.000 85	0.925 1–1.024 9	0.000 63
0.716 7–0.730 0	0.000 83	1.025 0–1.074 9	0.000 61
0.730 1–0.742 4	0.000 81	1.075 0–1.124 9	0.000 59

Table 28.23 CORRECTION COEFFICIENTS FOR COAL TAR FUELS[18]

Type	*Specific gravity correction coeff. per* 1 °C
CTF 50+100	0.000 76
CTF 200	0.000 63
CTF 250	0.000 58
CTF 300	0.000 50
CTF 400	0.000 49

(C) SPECIFIC HEAT

For petroleum oils.[17]

$$\text{specific heat} = \frac{1.69 + 0.0034t}{\sqrt{d}} \text{ kJ kg}^{-1} \text{ K}^{-1}$$

$+2\%$ for naphthenic base crudes
-2% for paraffin base crudes

where

d = specific gravity 15.6/15.6 °C (60/60 °F)
t = temperature, °C

For coal tar fuels.[18]

$$\text{Specific heat} = 1.46 - 1.68 \text{ kJ kg}^{-1} \text{ K}^{-1}$$
$$(0.35\text{–}0.40 \text{ Btu lb}^{-1} \text{ F}^{\circ -1})$$

(D) THERMAL CONDUCTIVITY

For petroleum oils:[17]

$$K = \frac{0.1184 - 0.0000\,195T}{d} \text{ W m}^{-1} \text{ K}^{-1}$$

$$\text{or } \frac{0.821 - 0.000\,244t}{d} \text{ Btu (ft}^2 \text{ h)}^{-1} \text{ (°F in}^{-1})^{-1}$$

where

T = temperature, °C
t = temperature, °F

For tar fuels,[18]

$K = 0.138\text{–}0.147$ W m^{-1} K^{-1}
or 0.96–1.02 Btu (ft^2 h)$^{-1}$ (°F in^{-1})$^{-1}$

(E) VISCOSITY

British fuel oil kinematic viscosities are quoted in centistokes (cSt) at a specified temperature (BS 4708: 1971), and, formerly, by seconds Redwood I at 100°F (Redwood II is approximately 1/10 seconds Redwood I). Coal tar fuels are numbered according to the temperature in °F at which their viscosity is 100 seconds Redwood I, i.e. about 24 cSt at 37.8 °C. Suitable handling temperatures are quoted for each class of fuel.

Table 28.24 VISCOSITY OF LIQUID FUEL

Class	*Kinematic viscosity*		*Storage* °C	*Pumping* °C	*Atomizing temperature* °C
	Temperature °C (°F)	cSt(10^{-2}m^2s^{-1})			
Gas oil	37.7 (100)	4	—	—	Ambient
Light fuel oil	82.2 (180)	12.5	10	10	55
Medium fuel oil	82.2 (180)	30	25	30	90
Heavy fuel oil	82.2 (180)	70	35	45	125
CTF 50	37.8 (100)	13	—	—	15
CTF 100	37.8 (100)	24	35	35	38–50
CTF 200	37.8 (100)	300	35	40	80–95
CTF 250	30	35 000	55	75	115–130
CTF 300	55	25 000	85	100	140–155
CTF 400	—	—	135	150	190–205

(F) FLASH POINT

Special precautions are required by statute[20] for liquids with flash points below 32 °C (90 °F). Typical values for fuels are:

	Flash point °C (°F)
Petrol	−40 (−40)
Kerosine	+43 (+110)
All coal tar fuels	over 65 (150)
Gas oil	77 (170)
Light fuel oil	82 (180)
Medium fuel oil	93 (200)
Heavy fuel oil	115 (240)

28.3.2 Gaseous fuels

Table 28.25 shows the properties of most fuel gas constituents.

With the advent of both SI units and natural gas there have been a number of changes in both nomenclature and practice.[21]

Metric standard reference conditions for gas (st) The standard reference conditions for gas are now 15 °C and 1013.25 mbar and *dry*, as defined by the International Gas Union. This is to be compared with the Imperial Standard conditions ISC (or more commonly STP) of 60 °F (15.6 °C), 30 inches Hg (equivalent to 1013.75 mbar) usually applied to the gas *saturated with water vapour*, and Normal Temperature and Pressure NTP of 0 °C, 760 mm Hg (equivalent to 1013.25 mbar) also referred to as STP in BS 350:1963.

Pure gaseous fuels are rarely used in metallurgical heating, but the performance of industrial fuels can be predicted from their properties. There is a considerable range in analysis possible with industrial fuels, and the ones given below are considered typical.

(A) BLAST FURNACE GAS

This is the byproduct of iron or ferromanganese production, obtained from the top of the furnace after cooling and suitable dust removal. Injection processes for steam, oil, coal, gas and oxygen tend to vary the typical analyses. Below 3.7 MJ m^{-3} (100 Btu ft^{-3}) calorific value the gas should be enriched[22] or pre-heated before combustion.

The specific gravity relative to air varies from 1 to 1.07.

Table 28.25 PROPERTIES OF CONSTITUENTS OF GASEOUS FUELS

Gas	*Formula*	*Specific gravity (air = 1)*	*Gas density (calc.)*			*Calorific value* MJ m^{-3} (st) *dry*	*Calorific value* Btu ft^{-3}	
			kg m^{-3} *NTP dry*	lb ft^{-3} *dry*	*STP sat.*		*STP sat. gross*	*STP sat. net*
Oxygen	O_2	1.1044	1.428	0.08457	0.08393	—	—	—
Atmospheric nitrogen	N_2	0.9723	1.257	0.07446	0.07400	—	—	—
Air	—	1.0000	1.293	0.07657	0.07607	—	—	—
Carbon dioxide	CO_2	1.5185	1.963	0.11628	0.11509	—	—	—
Carbon monoxide	CO	0.9663	1.250	0.07400	0.07354	12.04	318	318
Hydrogen	H_2	0.06958	0.090	0.00533	0.00607	12.12	320	270
Methane	CH_4	0.5533	0.715	0.04237	0.04247	37.68	995	895
Ethane	C_2H_6	1.0371	1.341	0.07941	0.07887	65.52	1730	1580
Propane	C_3H_8	1.5210	1.966	0.11646	0.11526	93.87	2479	2282
Butane	C_4H_{10}	1.9358	2.503	0.14823	0.14648	117.23	3095	2848
Acetylene	C_2H_2	0.8980	1.161	0.06876	0.06840	55.00	1452	1402
Ethylene	C_2H_4	0.9675	1.251	0.07409	0.07363	59.08	1560	1460

Table 28.25 PROPERTIES OF CONSTITUENTS OF GASEOUS FUELS—*continued*

Gas	*Formula*	*Specific gravity (air = 1)*	*Gas density (calc.)* kg m^{-3} *NTP dry*	lb ft^{-3} *dry*	*STP sat.*	*Calorific value* MJ m^{-3} (st) *dry*	*Calorific value* Btu ft^{-3} *STP sat. gross*	*STP sat. net*
Propylene	C_3H_6	1.451 2	1.876	0.111 13	0.110 03	87.11	2 300	2 150
Butylene	C_4H_8	1.935 0	2.501	0.148 17	0.146 43	115.13	3 040	2 840
Benzene	C_6H_6	2.693 8	3.483	0.206 26	0.203 51	141.64	3 740	3 590
Water	H_2O	0.621 8	0.804	—	0.047 61	—	—	—
Hydrogen sulphide	H_2S	1.176 2	1.521	0.090 07	0.089 33	23.86	630	580
Sulphur dioxide	SO_2	2.211 5	2.860	0.169 33	0.167 21	—	—	—

Table 28.26 BLAST FURNACE GAS ANALYSES (MODERN FURNACES WITH OIL INJECTION)

% Analysis by volume CO	CO_2	H_2	N_2	*Calorific value STP sat.* MJ m^{-3}	Btu ft^{-3}
20–23	20–22	3–5	52–55	2.9–3.2	79–86

(B) LIQUEFIED PETROLEUM GAS, LPG

This type of industrial gas is a byproduct of the petroleum industry. These gases are transported in liquid form and vaporized before combustion. They may be used directly, mixed with other gases or distributed as a mixture with air.[23] The liquids have large coefficients of thermal expansion.

Table 28.27 TYPICAL RICH GASEOUS FUELS

	Natural gas	*LPG*[24, 25] *Propane*	*Butane*	*Refinery gas*[26] *Low*	*Medium*	*High*
		% Analysis by volume				
H_2	—	—	—	56	22	0.5
CH_4	86–90	—	—	12	22	22
C_2H_6	2.9–5.3	2	0.5	13	22	25
C_3H_8	0.5–1.3	87	10	13	18	36
C_4H_{10}	0.2–0.3	6	85	2	3	3
C_2H_4	—	2	0.5	1	3	2
C_3H_6	—	2	3	1	7	9
C_4H_8	—	1	1	1	2	2
N_2	1.2–6.8	—	—	1	1	0.5
Specific gravity (air = 1.0)	0.585–0.631	1.528	1.872	0.531	0.876	1.180
Calorific value, Gross						
MJ m^{-3} (st)	37.9–39.2	92.7	111.7	36.5	55.1	72.3
Btu ft^{-3}	1 016–1 051	2 486	2 995	977	1 478	1 938
MJ kg^{-1}	—	49.4	48.6	55.8	51.3	49.9
Net						
MJ m^{-3}	—	85.4	102.9	32.5	50.4	66.4
Btu ft^{-3}	—	2 289	2 758	872	1 352	1 780
MJ kg^{-1}	—	45.5	44.8	49.8	46.9	45.8
Liquid specific gravity	—	0.51	0.58	—	—	—
Latent heat of vaporization kJ kg^{-1}	—	426	391	—	—	—
Vapour pressure at 37.8 °C bar (a)	—	16.1	5.86	—	—	—
Liquid coefficient of Cubical expansion per °C		0.0016	0.0011			

(C) NATURAL GAS

Natural gas, supplied from the North Sea gas fields, is a rich hydrocarbon gas, predominantly methane, which is now superseding the previous town gas. Large users have been supplied on an interruptible basis often necessitating the use of dual-fuel burners.[27] Its limits of inflammability are narrow (*see* Table 28.30) and flame speed low when compared with town gas.

(D) PRODUCER GAS

Producer gas[28] is formed by partial oxidation of a solid fuel bed. The process is modified by the introduction of steam (blue water gas) and by thermal cracking of a hydrocarbon fuel such as natural gas, propane, butane, petroleum distillate, gas oil or heavy fuel oil (carburetted water gas).

Normally oxidation of the fuel bed is carried out with air, but total gasification processes also use oxygen. Tar in hot raw producer gas may increase the calorific value to around 74 MJ m^{-3} (200 Btu ft^{-3}).

Table 28.28 ANALYSES OF PRODUCER GAS

Representative of type	*Gas analysis (% volume)*					*Specific gravity (air = 1.00)*	*kJ m^{-3} sat. at 15.6 °C (Btu/SCF sat.)*	
	CO	CO_2	H_2	CH_4	N_2		*Gross*	*Net*
Producer gas								
Coke, no steam	31.3	2.1	0.5	—	66.1	0.978	3 770 (101.2)	3 763 (101.0)
Coke, steam	29.3	5.6	12.4	—	52.7	0.889	4 952 (132.9)	4 720 (126.7)
Anthracite	24.0	7.5	16.5	1.2	50.8	0.858	5 253 (141.0)	4 900 (131.5)
Bituminous coal	27.0	4.5	14.0	3.0	51.5	0.857	5 980 (160.5)	5 707 (150.5)
Blue water gas								
Coke, steam	43.5	3.5	47.3	0.7	5.1	0.560	11 050 (296.7)	10 150 (272.4)
Fixed bed slagging gasifier	65.5	4.0	29.0	0.4	1.0	0.727	11 380 (305.5)	10 830 (290.6)

(E) REFINERY GAS

Refinery gas may be a byproduct of distillation, cracking or reforming of gas in the petroleum industry. Typical gases are shown in Table 28.27.

(F) TOWN GAS

Town gas used to be made almost exclusively by coal carbonization. Now it can be made of a complex mixture of gases,[29] including coke oven gas, natural gas, liquefied petroleum gas, water gas, refinery gas, reformed hydrocarbon fuels or hydrocarbon fuels diluted with air. To make gas safer the $CO + H_2O = CO_2 + H_2$ shift reaction may be used to reduce the quantity of CO present.[30] CO_2 may be removed to increase calorific value and to reduce the specific gravity.

Gases are grouped according to the Wobbe index.

$$\text{WI} = \frac{\text{gross calorific value MJ m}^{-3}\text{ (st) dry}}{\sqrt{[\text{specific gravity (air} = 1.0)]}}$$

or

$$\frac{\text{gross calorific value Btu ft}^{-3}\text{ STP (ISC) sat.}}{\sqrt{[\text{specific gravity (air} = 1.0)]}}$$

Gas group	*Wobbe index* Btu ft^{-3} STP *sat.*	MJ m^{-3}(st) *dry*
G3	800±40	30.4±1.52
G4	730±30	27.7±1.14
G5	670±30	25.4±1.14
G6	615±25	23.3±0.95
G7	560±30	21.3±1.14
Natural gas	1 335±5%	50.68±5%

Table 28.29 shows the typical properties of some manufactured gaseous fuels.

Table 28.29 PROPERTIES OF SOME MANUFACTURED GASEOUS FUELS

	Horizontal retort	*Intermittent vertical chamber*	*Coke oven*	*Continuous vertical retort*	*Low temp.*	*Carburetted water gas*	*Butane air*	*CWG, CO_2, CO conv. butane enriched*
				% Analysis by volume				
CO	7.20	13.04	7.72	14.06	3.68	31.29	—	4.0
CO_2	1.72	3.01	2.39	3.49	4.89	4.59	—	21.0
H_2	56.07	50.24	48.02	55.99	16.58	36.48	—	49.7
CH_4	26.52	19.11	25.94	17.81	33.52	8.04	—	7.0
N_2	1.88	7.98	9.15	4.35	25.80	8.41	57.67	7.0
O_2	0.14	1.14	0.68	0.18	2.80	0.72	15.33	—
$C_nH_m^*$	4.0 ($C_{2.5}H_5$)	3.10 ($C_{2.5}H_5$)	4.34 ($C_{2.5}H_5$)	2.45 ($C_{2.5}H_5$)	3.04 (C_4H_8)	8.75 ($C_{2.5}H_5$)	—	8.6 ($C_{2.5}H_5$)
C_nH_{2n+2}	2.47 (C_2H_6)	2.38 (C_2H_6)	1.76 (C_2H_6)	1.67 ($C_{2.5}H_7$)	9.69 ($C_{2.5}H_7$)	1.72 (C_2H_6)	27.0 (C_4H_{10})	2.7 (C_4H_{10})
Calorific value, Gross								
MJ m^{-3}	21.8	18.4	20.5	18.0	25.9	18.4	31.1	18.2
Btu ft^{-3}	586	494	550	483	695	495	836	488
Net								
MJ m^{-3}	19.5	16.5	18.4	16.1	23.5	16.9	28.6	16.4
Btu ft^{-3}	523	442	493	432	630	455	769	439
Specific gravity	0.375	0.465	0.455	0.422	0.771	0.655	1.252	0.655
Wobbe index								
MJ m^{-3}	35.6	27	30.4	27.7	29.5	27.3	27.8	22.5
Btu ft^{-3}	956	724	816	743	792	734	747	603

* C_nH_m refers to the average analysis of the mixture of remaining hydrocarbons.

For a given piece of equipment the gases within a group as defined by the Wobbe index are interchangeable[31] without burner and nozzle adjustment. However, when changing gaseous fuels, blow-off and flame speed and flash-back must be carefully considered.

(G) ANALYSIS OF FUEL GASES[32]

The following constituents may also be found in fuel gases.

Dust is found in insufficiently cleaned blast furnace and producer gas.

Naphthalene in town gas should be below 23 mg m^{-3} (1 gr per 100 ft^3) in winter and 46 mg m^{-3} (2 gr per 100 ft^3) in summer.

Hydrogen sulphide should not be present in town gas.

7–20 g m^{-3} (300–900 gr per 100 ft^3) may be present in unpurified coal gas.

45 g m^{-3} (2000 gr per 100 ft^3) may be present in refinery gas.

Organic sulphur Up to 1 g m^{-3} (40 gr per 100 ft^3) may be present in town gas. This figure will be lowered by oil washing, benzole stripping, etc. Below 0.02% by weight sulphur is usually present in LPG. Natural gas contains little organic sulphur, 0.3–9.0 ppm v/v and a limit of about 30 mg m^{-3} will be set.

Condensable vapours are chiefly benzene and toluene in carbonization gas, the quantity depending chiefly on temperature of carbonization, volatile matter in coal, and degree of benzole removal.

Tar may be found in producer gas, made from coal.

Water vapour The majority of fuel gases contain water vapour, hence the usual determinations used to assume that the gases were saturated with water vapour at 30 in Hg total pressure (1013.75 mbar) and at 60 °F(15.6 °C). Natural gas properties are quoted on a dry basis (st).

(H) LIMITS OF INFLAMMABILITY

The limits of inflammability[33] of gaseous fuels and vapours are shown approximately in Table 28.30.

Table 28.30 LIMITS OF INFLAMMABILITY

	% By volume in air	
	Lower limit	*Upper limit*
Acetylene	2.5	80
Blast furnace gas	35	74
Butane	1.9	8.5
Carbon monoxide	12.5	74
Carburetted water gas	5.5	36
Coal gas	5.3	32
Coke oven gas	4.4	34
Ethane	3.0	12.5
Hydrogen	4.0	75
Methane	5.3	15
Petrol	1.4	7.6
Producer gas	17	70
Propane	2.2	9.5
Water gas	7.0	72
Commercial butane	1.9	8.5
Commerical propane	2.4	9.5

These limits are affected by direction of propagation, temperature, pressure and inert diluents.

(I) OXYGEN AND PRE-HEAT

Regeneration to about 1100 °C and recuperation to about 800 °C as a mean of pre-heating combustion air are valuable methods of waste heat recovery in large furnaces. The recuperative burner can be employed on smaller furnaces.[34] Lean fuels such as blast furnace and producer gas can be pre-heated to about 500 °C without cracking, to raise the adiabatic flame temperature of the fuel.

Oxygen is available from 200 to 1700 tonnes per day units (700 m^3 t^{-1} STP). In bulk, oxygen must be handled in oil- and grease-free equipment. Pipelines are required to be of stainless or special carbon steel, the oxygen velocity should not exceed 8 m s^{-1}. Non-ferrous valves, flow controllers and water-cooled oxygen-free copper lance tips are desirable for controlling the flow of oxygen in refining processes.

Tonnage oxygen for steelmaking is normally supplied with a purity of 99.5% O_2 for the following purposes:

(a) Oxidation refining processes.
(b) Raising flame temperature.
(c) To obtain extra output from a given furnace system by burning more fuel per unit combustion space.[35,36,37]

(d) Reducing metallic losses, eg. electric steelmaking.
(e) Reducing nitrogen pick-up by metal from combustion air.

Tonnage oxygen for copper smelting, carried out outside the UK, is normally supplied with a purity of 95% O_2.

Use of oxygen lowers the volume of waste gases and hence the heat loss from a furnace as compared with atmospheric air for combustion. Oxygen enrichment of combustion air has a similar effect to increasing its pre-heat temperature.

The adiabatic flame temperature is a guide to the maximum furnace temperature obtainable from a fuel. Its value is lowered by the following conditions.

(a) Dilution with inert gases such as N_2, CO_2.
(b) Dissociation of H_2O and CO_2, particularly over 2000 °C.
(c) Heat loss by radiation.

Table 28.31 FLAME TEMPERATURES OF SOME GASES

	Gross calorific value of fuel		*Flame temperature* °C	
	MJ m^{-3}(st) *dry*	Btu per SCF *sat.*	*In air maximum*	*In oxygen including dissociation*
Acetylene	55.1	1452	2325	3200
Butane	117.5	3095	1895	—
Butylene	115.4	3040	1930	—
Carbon monoxide	12.07	318	1950	—
Ethane	65.7	1730	1895	—
Ethylene	59.2	1560	1975	—
Hydrogen	12.15	320	2045	2200
Methane	37.8	995	1880	—
Propane	94.1	2479	1925	2500
Propylene	87.3	2300	1935	—
Coal gas	21.1	560	2045	2100
Coal gas	18.0	475	2045	—
Blue water gas	11.2	295	2080	—
Producer gas	6.3	165	1800	—
Producer gas	4.8	128	1690	—
Blast furnace gas	3.5	92	1460	—

28.3.3 Fuel material and energy data for various metallurgical processes

The iron and steel industry has much published information,[38] particularly regarding large-scale processes. Non-ferrous processes are in general carried out on a much smaller scale, and comparisons are more difficult to make because of varying conditions of production.

(A) COKE PRODUCTION

Modern coke ovens are compound-fired by coke oven gas, and pre-heated blast furnace gas. Coke breeze is used in sinter production. A surplus of coal tar fuel and coke oven gas is available for other purposes.

Developments[40] to extend the range of coals for producing metallurgical coke or to reduce energy usage or pollution include: coal blending, pre-heat of the coal charge, stamping of the charge, programmed heating, and dry cooling of the hot coke.

Typical figures are shown in Table 28.32.

Table 28.32 ENERGY IN COKE PRODUCTION[40]

Dry coal carbonized	1.000 tonne
Blast furnace coke	690 kg
Coke breeze	60 kg
Oven underfiring fuel	2 500 MJ (24 therms)
Power required	49 MJ (13.8 kWh)
Steam required	620 MJ (300 kg)
Crude tar	43 kg
Crude benzole	11.7 kg
Sulphate of ammonia	8.5 kg
Coke oven gas	6 040 MJ (300 m^3)
Dry cooling of coke saves	1 300 MJ
Coal pre-heating saves	190–330 MJ
Programmed heating of coke ovens saves	10%

Formed-coke processes with calcining, in relation to the blast furnace, probably result in a 5% increase in total energy used per tonne of iron.[40]

(B) ORE PREPARATION

Mixes vary according to materials available and iron quality required but the national average in Table 28.33 will indicate the order of constituents used for sinter for ironmaking.

Table 28.33 AVERAGE MATERIALS USED IN SINTER MAKING

Materials	*Sinter* (kg $tonne^{-1}$)
Home iron ore	273
Imported iron ore	721
Imported manganese ore	2
Pyrites residue	10
Scale	41
Slag	2
Flue dust	4
Iron and steel scrap	2
Other Fe-bearing materials	45
Limestone and dolomite	100
Other burden material	16
Coke and coke breeze	82
Total	1 296
Coke oven and blast furnace gas igniter	170 MJ $tonne^{-1}$ (1.6 therm ton^{-1}) 45 MJ m^{-2} bed surface[39]
Power consumed	79 MJ $tonne^{-1}$ (22 kWh)

(C) IRONMAKING

Plants may use home ore, foreign ore or mixed ore; Table 28.34 gives national averages showing the general quantities of materials used.

Table 28.34 AVERAGE MATERIALS USED IN THE UK FOR IRONMAKING, kg TONNE^{-1}

Material	*Steelmaking*	*Foundry*	*Ferro-alloys*	*Total average*
Home iron ore	14	—	—	14
Imported iron ore	331	312	—	328
Manganese ore	6	31	1775	21
Sinter	1320	1292	—	1311
Limestone and dolomite	39	76	137	41
Scrap	6	53	42	9
Other materials	53	70	55	53
Total	1771	1834	2009	1777
Coke rate	576	702	1525	587

The modern blast furnace has a high thermal efficiency. Improvements of the economics of the blast furnace ironmaking route are therefore directed towards reducing the capital investment, hence the trend to larger production units, and utilizing the cheapest sources of energy compatible with good operation.[36] Oxygen injection in the blast increases the production rate, a one percentage point increase in the blast oxygen analysis increases production by 6% with an ultimate limit[41] of 26% oxygen in the blast. Fuel injection lowers the coke rate with coke replacement ratios of 0.95 to 1.5. Fuel oil is used mostly, though gas[43] pulverized coal,[44] coal-oil slurries and coal tar are all proven candidates.[36] Details of operation of modern blast furnaces[42] are shown in Table 28.35.

Table 28.35 MODERN BLAST FURNACE OPERATION[42]

Dry coke kg t^{-1} hot metal	405–440
Blast Nm^3 t^{-1} hot metal	1020–1690
Oxygen enrichment Nm^3 t^{-1} hot metal	0–30
Oil injected kg t^{-1} hot metal	40–120
Moisture kg t^{-1} hot metal	12–35
Blast temperature, K	1330–1550
Tuyere pressure bar gauge	2–3.4
Top pressure bar gauge	0.3–2.2
Pig iron tonnes per day	2500–9900

Direct reduction processes use natural gas or coal to reduce iron ore to sponge iron, suitable for electric furnace melting. Reported energy requirements[45] are in the range 13.8–15.9 GJ tonne^{-1} for the reduction process. The total energy requirement of the direct reduction electric arc furnace route is similar to that of the blast furnace–basic oxygen furnace route (16–20 GJ t^{-1}).

(D) FERROUS CASTINGS

The cupola is largely used in foundries for melting cast iron. The main raw materials are pig iron, cast iron and steel scrap, limestone and coke.

Cold-blast cupolas are being modified to divided blast[46] in which the air is introduced at two levels giving savings of 30% on coke rate and increasing melting rate by 20%. Recuperative hot blast (300–760 °C) cupolas with long daily melting campaigns have total foundry energy requirements 30% less than cold blast or electric melting.[47] Oxygen enrichment[37] of the blast (2%) can benefit quality melting rate and temperature. Electric induction[48,49] melting accounts for 10% of metal melted. Some electric arc furnaces[50] are used for melting awkward shaped scrap. With cold blast cupolas, additions and super-heating in an electric induction furnace (duplexing) can give savings. The cokeless cupola[51] using propane oil or natural gas is of interest in countries with excess of high CV gas. The oil-fired rotary furnace can be economical in a small foundry.[52] Emission of pollutants from foundries will receive increasing attention.[47]

Reduction of metal recycled as foundry returns (Table 28.36) has great potential for reducing the total energy used.

Table 28.36 AVERAGE MATERIALS USED IN IRON FOUNDRIES, kg TONNE^{-1} OF CASTINGS

Scrap	*Pig iron*	*Foundry returns*	*Coke*	*Coal*
595	405	469	264	32

Table 28.37 ENERGY USED IN IRONMAKING PER TONNE OF MOLTEN METAL

Process	*Coke* kg	*Electricity* kWh	*Gas or oil*
Cold blast cupola[47]	~200		
Divided cold blast cupola[46,47]	~140		
Recuperative hot blast cupola[47]	~90		
Cokeless cupola[47,51]			
with gas			34 Nm^3 propane (3.2 GJ)
with oil			80 kg oil (3.4 GJ)
Electric coreless[48]		650	
Induction			
Holding		30	
Super-heating		60–75	
Electric arc[50]		550–625	
Duplexing		50–60	
Holding		50–150	
Rotary furnace[52]			125–216 kg oil
Oil-fired			(5.4–9.3 GJ)

Table 28.38 INDUCTION MELTING FURNACES[53]

Rating kW	*Coreless melting furnaces*			
	Production rate		*Average furnace capacity*	
	50 Hz kg h^{-1}	150 Hz kg h^{-1}	50 Hz kg	150 Hz kg
200	350	320	—	600
300	550	500	2 100	1 000
400	720	630	2 700	1 200
500	860	770	3 000	1 500
1 000	1 800	1 600	8 000	2 600
2 000	3 600	3 200	15 000	5 000
4 000	7 700	—	27 000	—

Rating kW	*Channel furnaces* (50 Hz)		
	Production rate		*Average capacity* kg
	Melting kg h^{-1}	*Super-heating* kg h^{-1}	
300	800	500	9 000
500	1 400	850	15 000
1 000	2 800	1 800	25 000
2 000	5 900	4 000	75 000
5 000	13 600	9 000	200 000

(E) NON-FERROUS MELTING

Non-ferrous industry usually operates on a smaller scale than the steel industry, hence specific fuel consumptions are higher than for steelmaking despite a lower required melt temperature. Gas-fired furnaces are described and assessed in reference 34.

Table 28.39 TYPICAL NON-FERROUS FUEL CONSUMPTION

Type of furnace	*Capacity* kg (lb)	*Alloy*	*Fuel* MJ tonne^{-1} (therm ton^{-1})
Crucible	50 (100)	Aluminium	23 000 (220)
Bale out	200 (400)	Aluminium	4 000–7 000 (40–70)
Reverberatory	600 (1 200)	Aluminium	2 600–4 000 (25–40)
Reverberatory	2 500 (2.5 ton)	Aluminium 1 tonne h^{-1}	3 200 (31)
Reverberatory	—	Bronze $2\frac{1}{2}$ tonne h^{-1}	3 700 (36)

Mains frequency induction melting furnaces can be used for non-ferrous melting.

Table 28.40 MAINS FREQUENCY INDUCTION MELTING[54]

Capacity kg (lb) *Rating* kW	150 (300) 25		1200 (2640) 120		4000 (8814) 300	
	kg h^{-1} (lb h^{-1})	MJ t^{-1} (kWh ton^{-1})	kg h^{-1} (lb h^{-1})	MJ t^{-1} (kWh ton^{-1})	kg h^{-1} (lb h^{-1})	MJ t^{-1} (kWh ton^{-1})
Copper	100 (220)	885 (250)	340 (750)	1 130 (320)	900 (1 984)	1 150 (325)
Brass	145 (320)	700 (200)	520 (1 150)	780 (220)	1 400 (3 086)	740 (210)
Aluminium	60 (132)	1 600 (450)	295 (650)	1 400 (400)	720 (1 587)	1 400 (400)
Zinc	180 (400)	500 (140)	885 (1 950)	460 (130)	2 200 (4 850)	440 (125)

(F) STEELMAKING[50,55,56,57,58]

The raw materials of steelmaking are principally basic iron, cold or molten, and scrap together with various additions as shown in Table 28.41 for national averages. Production from hot metal and scrap in oxygen converters and from scrap in electric arc furnaces now predominates.

Depending on the proportions of hot metal to scrap and compositions oxygen converters require 45–70 Nm^3 of oxygen per tonne metal.

Arc furnaces ranging in capacity from 10 to 200 tonnes have maximum power requirements at meltdown of 600 to 300 kW t^{-1} respectively.[50] The energy requirement is about 2.3 GJ t^{-1} (650 kWh t^{-1}) of which about 720 MJ t^{-1} (200 kWh t^{-1}) is provided by chemical reactions and combustion of carbon in the metal and electrode carbon, which use about 15 m^3 t^{-1} of oxygen. A reduction of the electrical power input by 400 MJ t^{-1} (110 kWh t^{-1}) can be achieved by preheating the scrap metal charge.

An open hearth furnace melting scrap uses 6.2 GJ tonne^{-1} (60 therms ton^{-1}); with 60% hot metal uses 3.7 GJ tonne^{-1} (36 therms ton^{-1}); with 70% hot metal and 40 m^3 tonne^{-1} of oxygen uses 2.4 GJ tonne^{-1} (23 therms ton^{-1}).

Table 28.41 AVERAGE MATERIAL CONSUMED kg TONNE^{-1} OF STEEL PRODUCED[38]

Process	*Iron*		*Scrap*		*Oxides*	*Finishings*	*Fluxes and fettling materials*	*Total*
	Molten	*Cold*	*Steel*	*Cast iron*				
Oxygen converters	851	15	265	4	12	11	102	1 260
Electric arc	—	56	1 027	33	5	29	57	1 207
Basic open hearth	426	104	532	50	62	5	82	1 261

The ancillary steelmaking energy requirements are as follows:

Lime burning	4700 MJ t^{-1} (45 therm ton^{-1})
Hot metal mixer (inactive)	155 MJ t^{-1} (1.5 therm ton^{-1})
Ladles, stopper rods	145 MJ t^{-1} (1.4 therm ton^{-1}) steel
Refractory repairs, heating up	145 MJ t^{-1} (1.4 therm ton^{-1}) steel
Waste heat boiler power	40 MJ t^{-1} (5 kWh per 1 000 lb) steam
Waste heat recovery	670 kg (1 500 lb) steam per tonne ingot
Cranes	14 MJ (4 kWh) per tonne ingot
Kaldo vessel rotation	7 MJ (2 kWh) per tonne ingot
Waste gas cleaning plant	25 MJ (7 kWh) per tonne ingot
Other steelworks auxiliaries	7 MJ (2 kWh) per tonne ingot
Oxygen production	2–2.5 MJ m^{-3} (16–20 kWh per 1 000 ft^3) oxygen
Arc furnace electrodes	5 kg per ingot tonne
Arc furnace electrode	4 kg per ingot tonne for large furnace using oxygen
Steam for liquid fuel	0.9 kg per litre fuel for pumping, heating, atomising

(G) CONTINUOUS CASTING

Power required, total	43 MJ t^{-1} (12 kWh ton^{-1})
Ladle and tundish heating	155 MJ t^{-1} (1.5 therm ton^{-1})
Yield of slab, bloom, billet	92–98% depending on ladle size

Continuous casting to produce semi-finished products can show considerable energy saving and increased yield compared with conventional, casting, soaking and primary mill practice.

(H) ENERGY REQUIREMENTS OF VARIOUS METAL HEATING PROCESSES[59,60,61,62,63,64]

Ingot soaking pits

Lowest possible	100 MJ t^{-1} (1 therm ton^{-1})
Good practice, hot metal	400 MJ t^{-1} (4 therm ton^{-1}) (3 h soaking)
Good practice, cold metal	2 000 MJ t^{-1} (20 therm ton^{-1}) (15 h soaking)
Electric, short track time	106 MJ (30 kWh) per tonne
Electric, large ingots	320 MJ (90 kWh) per tonne
Electric cold	1 200 MJ (330 kWh) per tonne
Auxiliary power required soaking pits	10 MJ (2.75 kWh) per tonne
Ingot stocking	4.3 MJ (1.2 kWh) per tonne
Scarfing	7 MJ (2 kWh) per tonne

Slab reheating furnaces

	Throughput t h^{-1}	*Nominal metal thickness* mm (in)	MJ t^{-1}	therm ton^{-1}
1 zone	20	8 (3)	1 500	(15)
2 zone	50	13 (5)	2 100–2 500	(20–24)
3 zone	100	20 (8)	2 400–3 300	(23–32)
5 zone	200	30 (12)	3 000–4 100	(29–40)

Hearth loading 350–1 000 kg m^{-2} h^{-1}
Power required 32 MJ t^{-1} (9 kWh ton^{-1})

Batch furnaces

	Hearth loading kg m^{-2} h^{-1} (lb ft^{-2} h^{-1})	*Temperature* °C	*Charge* t h^{-1}	MJ t^{-1} (therm ton^{-1})
Bogie furnace	245 (50)	—	12	2 100 (20)
Normalizing	200–300 (40–60)	1 000	—	1 700 (16)
Batch forging furnace	300–400 (60–80)	—	—	6 000–17 000 (60–160)
Tempering furnace	150–300 (30–40)	500	—	800 (8)
Annealing coils	—	750	11	650 (7)

Billet and bloom reheating furnaces

Continuous billet 1 400 MJ t^{-1} (14 therm ton^{-1})
Continuous bloom reheater 2 500 MJ t^{-1} (25 therm ton^{-1})

(I) ROLLING OF METAL

Table 28.42 ROLLING MILL POWER REQUIRED

	MJ t^{-1} (kWh ton^{-1})	
Slabbing mill	57 (16)	Ingot
Continuous roughing and billet mill	124 (35)	Bloom
Scarfing machine	7 (2)	Bloom
Plate mill	354 (100)	Plate
Roughing mill	57 (16)	Slab
Finishing mill	159 (45)	Strip
Mill auxiliaries	85 (24)	Slab
Descaling	39 (11)	Slab
Universal slab mill	57 (16)	Slab
Strip mill	248 (70)	Strip

Power consumptions for small mills for various sections are not quoted because of variability in reduction and other working conditions.

(J) FLUE GASES

Combustion of most fuels results in the formation of CO_2, SO_2, N_2 and H_2O. Excess air is shown by the presence of O_2 in low-temperature flue gas. Incomplete combustion is shown by the presence of CO and H_2. *See* references 65 and 66 for verification of the accuracy of the analysis of a flue gas and charts illustrating the effect of excess air and waste gas temperatures on the loss of heat up the stack.

(K) ENERGY CONSERVATION

There is much variety in processes and proportions and compositions of materials for the making of iron and steel and the contributions of all the sources of energy need to be calculated when assessing them.[67,68] With the rise in the real cost of energy, a determination of all the energy inputs[47] necessary for a process, i.e. including the energy inputs for capital plant transport materials, etc. gives a useful perspective for long-term planning.

National energy audits[40,47,69,70,71] have clearly shown that substantial reductions in energy usage can be made simply by good housekeeping: checking insulation standards;[72] analysing combustion products and regulating inputs to burners accordingly;[65,66] scheduling furnaces to keep holding times to a minimum; minimizing the recycle of metal, e.g. foundry returns.[47]

About 40% of the heat input to reheating furnaces leaves in the waste gases and can be used to pre-heat the combustion air in a recuperator or to raise steam. Older furnaces can be relined with ceramic fibre insulation and dampers fitted to control air inleakage.

The chemical and sensible heat of waste gases from oxygen converters and arc furnaces can be used to pre-heat scrap or raise steam.[73]

Analyses of the potential for energy conservation in the iron and steel industry are given in references 73 and 74, and in the aluminium and copper industries in references 75 and 76.

Pollutant emission control in an integrated works now uses 45 kWh tonne^{-1} of steel and improved standards, particularly in cokemaking, will increase this to 119 kWh tonne^{-1}, which corresponds to 550 − 1200 kWh tonne^{-1} of dust.[77] The total power used in non-electric steelmaking is about 390 kWh tonne^{-1}.

Reducing the number of processes in a production system is an effective energy saver.

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29 Heat treatment

29.1 Chemistry of controlled atmosphere processes

Controlled atmospheres are used to ensure that the heated metal has the desired surface characteristics[1–4]. Furnace atmospheres may be used to prevent or promote reactions at metal surfaces and to eliminate subsequent cleaning processes. Cementation by carbon and nitrogen and freedom from oxidation may also be achieved by the use of suitable molten salt mixtures as an alternative to controlled atmospheres.

The reactions that take place may be classified broadly into three groups.

Group I metal + gas A = metal compound + gas B

e.g. $Fe + H_2O = FeO + H_2$

$Cu + H_2S = CuS + H_2$

Group II alloy + gas A = alloy + gas B

e.g. C (in Fe) + CO_2 = Fe + 2CO

O (in Cu) + H_2 = Cu + H_2O

Group III gas A + gas B = gas C + gas D (or solid D)

e.g. $CO_2 + H_2 = CO + H_2O$

$CH_4 = 2H_2 + C$

The compositions of these systems at equilibrium is determined from the reaction $A + B \rightleftharpoons C + D$ by the equation:

$$\frac{[C][D]}{[A][B]} = K_T$$

where the square brackets are activities, usually expressed as concentrations and K_T is the equilibrium constant at temperature T K. The effect of temperature on the equilibrium constant is given by:

$$\log_{10} K = \frac{-\Delta G \text{ (in calories)}}{4.576T} \quad \text{or} \quad \log_{10} K = \frac{-\Delta G \text{ (in joules)}}{19.146T}$$

ΔG is the free energy of the reaction and can be calculated from the relation

$$\Delta G = \Delta H - T\Delta S$$

using the tables in chapter 8 or from standard tabulations[5].

29.1.1 Group I

The stability of metal oxides at heat-treating temperatures is an important factor in controlled atmosphere processes. Dissociation pressures of the common metallic oxides are very low at normal heat treating temperatures (Figure 29.1) and deoxidation by treatment in an inert gas or *in vacuo* is not practicable. In the presence of a reducing gas such as hydrogen, oxides may be reduced; this forms the basis of many industrial processes such as the manufacture of certain metal and alloy powders. Where the dissociation pressure is high, the equilibrium concentration of oxidizing gas (e.g. H_2O) in relation to the reducing gas (e.g. H_2) may be quite high, while for oxides of low dissociation pressure, small traces of oxygen-bearing gases may be sufficient to promote their formation (Table 29.1).

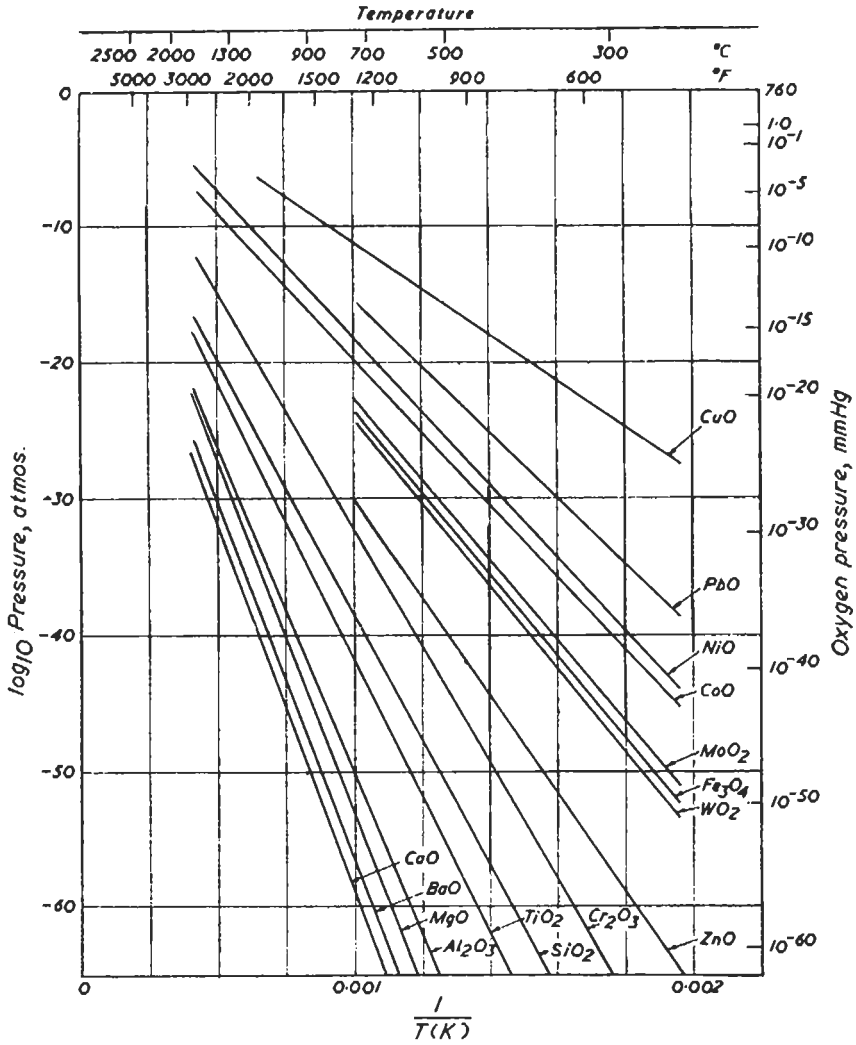


Figure 29.1 *Dissociation pressures of the common metallic oxides at normal heat-treating temperatures*

Table 29.1 OXIDATION OF METALS BY WATER VAPOUR AND BY CARBON DIOXIDE

	For oxidation at 727 °C	
Material	*% water vapour in hydrogen*	*% carbon dioxide in carbon monoxide*
Copper	> 99.999	> 99.999 9
Lead	99.982	99.989
Nickel	99.63	99.94
Iron	35.5	44.4
Carbon	24.4	31.0
Zinc	0.084	0.152
Chromium	0.001	0.002

29.1.2 Group II

In this type of reaction, the solid reactant is in solution in the parent metal and any excess of the constituent present as a separate phase in the alloy only enters into the reaction after solution in the matrix, e.g. carbon in iron or oxygen in copper.

$$C(\text{in Fe}) + CO_2 \rightleftharpoons Fe + 2CO$$

$$K = \frac{P_{CO}^2}{P_C \times P_{CO_2}}.$$

where P_C is dependent upon the concentration of carbon in solution in the iron, and this in turn determines the equilibrium ratio of P_{CO2}^2/P_{CO_2}. Reactions of this type are important in the heat treatment of carbon steels, where decarburization must be prevented, and in the annealing of tough pitch copper; they form the basis of industrial processes for the carburization and nitriding of steels, and the decarburization of white cast iron in the production of whiteheart malleable.

29.1.3 Group III

This group includes reactions which take place between constituents of the controlled atmosphere, a typical example being the water gas reaction:

$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$

Iron and nickel are both very active catalysts for the reaction, especially at their normal heat-treating temperatures, and the catalytic activity of metals for this and similar reactions may cause marked roughening of the metal surfaces. Other reactions included in this group are the 'cracking' of hydrocarbon gases and the breakdown of carbon monoxide, both of which may result in sooting. To prevent this the hydrocarbon (or carbon monoxide) is maintained below its equilibrium concentration for the reaction at the temperature of treatment.

29.1.4 Types of controlled atmospheres

Controlled atmospheres can be classified according to the source from which they are derived, and the composition of those most widely used is given in Table 29.2a. The fields of application of the various atmospheres overlap to a large extent, and the choice is often determined by economic considerations.

Table 29.2a INDUSTRIAL CONTROLLED ATMOSPHERES

Atmosphere	*Air/gas ratio*	*Approximate composition (volume%)*						*Approx. relative cost per unit vol.*	*Character-istics*	*Main applications*
		CO_2	CO	H_2	CH_4	N_2	*Dew point*			
Wet hydrogen	—	—	—	97.5–98.0 H_2 2.5–5.0 H_2O	—	—	—	250	Strongly reducing and decarburizing combustible	Decarburizing electrical sheet steel
Dry purified hydrogen	—	—	—	100	—	—	−50°C	250	Strongly reducing and explosive with air	High-temperature brazing of stainless steel and heat-resisting alloys
Cracked ammonia		—	—	75	—	25	−40°C	100	Strongly reducing and explosive with air	Bright annealing stainless and high carbon steels. Clean annealing brass

Table 29.2a INDUSTRIAL CONTROLLED ATMOSPHERES—*continued*

Atmosphere	*Air/gas ratio*	*Approximate composition (volume%)* Co_2	CO	H_2	CH_4	N_2	*Dew point*	*Approx. relative cost per unit vol.*	*Characteristics*	*Main applications*
Burnt ammonia	2.5/1 to 3.75/1	—	—	0–25	—	100–75	Room* temp. to −50°C	45	Reducing. Just combustible	Bright annealing carbon steels and non-ferrous metals. Clean annealing brass. Bright hardening on short time heating cycles
Nitrogen from ammonia	3.75/1	—	—	—	—	100	Room* temp. to −50°C	45	Inert and non-combustible	Bright annealing and bright and clean hardening carbon steels. Annealing silicon steel
Hydrogen from cracked ammonia separated by Ag–Pd membrane	—	—	—	100	—	—	−40°C	150	Strongly reducing and decarburizing	Heat treatment of pure metals at elevated temperature
Endothermic gas	2.2/1† (for natural gas)	0.25/0.4	20	40	0.5	40	−5 to +5°C	35	Strongly reducing, toxic and combustible	Bright and clean hardening. Brazing carbon and alloy steels. Carburizing
Partially burnt towns gas (natural gas)	6.5/1	4.0	9.5	15	—	71.5	Room* temp. to −50°C	20	Reducing. Just combustible and toxic	Bright annealing mild steel. Bright brazing and soldering mild steel. Malleablizing of cast iron
Completely burnt towns gas (natural gas)	4.5/1† 9/1	10.0	0.5–1.0	0.5–1.0	0.0	87–89	Room* temp. to −50°C	15	Slightly reducing. Non-combustible	Bright annealing copper and high copper brasses. Copper brazing
Nitrogen from towns gas, completely burnt and scrubbed of CO_2 and H_2O	4.5/1†	0.0	0.5–1.0	0.5–1.0	0.0	98–99	−50°C	12	Slightly reducing. Non-combustible	Bright annealing carbon steels and low alloy steels. Bright and clean hardening carbon steels
Completely burnt towns gas, treated ever hot charcoal	4.5/1†	0.0	20.0	2.0	0.0	78.0	Less than −20°C	10	Just combustible. Reducing and toxic	Bright annealing high carbon steels. Bright and clean hardening carbon steels. Diluent for carburizing atmospheres
Charcoal gas. High temperature external heating	—	—	34.0	—	—	66.0	Less than 20°C*	12	Reducing, combustible and toxic	Bright annealing carbon steels. Bright and clean hardening carbon steels. Diluent for carburizing atmospheres

* Dew point of wet gases may be reduced if required from room temperature to less than −50°C by means of suitable drying agents.
‡ Determined by the composition of the gas.

Table 29.2a INDUSTRIAL CONTROLLED ATMOSPHERES—*continued*

Atmosphere	*Air/gas ratio*	*Approximate composition (volume%)*						*Approx. relative cost per unit vol.*	*Character-istics*	*Main applications*
		CO_2	CO	H_2	CH_4	N_2	*Dew point*			
Organic liquids	—	—	—	—	—	—	—	60	—	For carburizing and carbo-nitriding steels
Vacuum	—	—	—	—	—	—	—	(Not comparable)	—	High temperature brazing and heat treatment of reactive metals such as titanium and zirconium; sintering of carbides and high temperature alloys; bright annealing of ferrous and non-ferrous alloys
Byproduct nitrogen from liquid oxygen plant; 0.2% O_2 removed over catalyst with added H_2	—	—	Few p.p.m.	2–5	—	95–98	−40°C	—	Slightly reducing, otherwise inert and non-explosive	Bright annealing of steel
Burnt towns gas scrubbed of CO_2, reformed with steam, scrubbed of CO_2 and H_2O	—	0.1	0.5	2–30	—	Re-mainder	−20°C	—	Reducing combustible if H_2 concentration high	Annealing of tin plate

* Dew point of wet gases may be reduced if required from room temperature to less than −50°C by means of suitable drying agents.
† Determined by the composition of the gas.

Table 29.2b

High purity bottled gases	*Dew point*	*Cost per unit volume*	*Characteristics*	*Main applications*
Nitrogen	<−70°C	300	Inert	Clean annealing; hardening
Hydrogen	<−70°C	300	Highly reducing and combustible	Hardening; annealing and brazing pure metals
Argon	<−70°C	3000	Inert	Titanium treatment
Ammonia	−40°C	70	Alkaline to toxic	Nitriding; carbonitriding

29.2 Heat treatment equipment

Different types of equipment have been found suitable for heat treatment of ferrous and non-ferrous metals. These are set out in Tables 29.3 and 29.4.

Induction hardening can use various generators. Typical efficiencies and the hardness depths to be expected are given in Table 29.5.

Table 29.3 FURNACES FOR FERROUS HEAT TREATMENTS

(*a*) *Annealing, normalizing, stress relieving and sintering*

Typical product	*Suitable equipment*
Forgings, castings, welded fabrications	Low thermal mass batch furnace (uncontrolled atmosphere)
Plates, tubes, coils *or* components in baskets	Continuous roller hearth furnace with controlled atmosphere
Stainless pressings	Cold wall vacuum furnace
Small components including sintering of powdered metal parts	Continuous mesh belt conveyor with reducing atmosphere
Wire immediately after drawing *or* wire for patenting	In-line induction heating *or* direct resistance heating
Wire and strip in coils	Retorted lift-off bell furnace
Strip, in-line	Continuous annealing line (heated by gas, electricity or transverse flux induction)

(*b*) *Hardening, carburizing, carbonitriding, austempering*

Typical product	*Suitable equipment*
Steel castings/larger forgings for through hardening	Low thermal mass batch furnace (preferably tilting hearth)
Components in high volume	Continuous cast link conveyor
Components requiring through hardening *or* surface hardening	Sealed quench furnace—components in baskets
Small components for hardening *or* (with salt bath) austempering	Shaker hearth furnace (with controlled atmosphere)
Long components, especially shafts for carburizing/ hardening	Controlled atmosphere pit furnace
Medium-carbon steel components including shafts and gears	Induction surface hardening
Components in small batches requiring various treatments	Fluidized bed furnace *or* set of salt baths
Tools and dies	High temperature salt baths[6]
Steels for aerospace applications, tools and dies	Cold-wall vacuum furnace with high pressure gas cooling

(*c*) *Tempering*

Typical product	*Suitable equipment*
Engineering components in high volume	Continuous slat belt conveyor furnace
Components in smaller batches	Vertical forced convection oven
Tools and dies (may require multiple tempering)	Cold-wall vacuum furnace with inert gas atmosphere

(*d*) *Nitriding and ferritic nitrocarburizing*

Typical product	*Suitable equipment*
Nitrided gears, shafts, etc. for nitriding	Vertical forced convection/pit oven with controlled atmosphere
High quality gears and shafts	Glow discharge nitriding plant
Components requiring sulfinuz, tufftride treatments, etc.	Salt bath[6] with appropriate salt
Mild steel components for nitrotec surface treatment	Forced convection oven with controlled atmosphere

Table 29.4 FURNACES AND EQUIPMENT FOR NON-FERROUS HEAT TREATMENTS

(*a*) *Annealing* *Typical product*	*Suitable equipment*
Copper wire in coil form	Retorted lift-off bell furnace *or* hot-wall vacuum furnace
Copper strip in coil form	Retorted lift-off bell furnace
Copper bars and tubes	Low thermal mass batch furnace
Continuous copper tube	In-line induction heater
Aluminium strip in coil form	Forced convection low thermal mass oven
Aluminium strip, continuous in-line	Transverse flux induction heater
Nickel alloys, titanium alloys, stainless steels	High temperature batch furnace
(*b*) *Solution treatment* *Typical product*	*Suitable equipment*
Aluminium diecastings in heat-treatable alloys	Vertical forced convection or pit-type batch oven
Aluminium forgings for aerospace applications	Elevator oven, quench tank at floor level
Aluminium extrusions, quenched at the die	(Avoids the need for separate solution treatment)
(*c*) *Ageing* *Typical product*	*Suitable equipment*
Aluminium extrusions, quenched at the die	Large 'walk-in' convection oven
Titanium, stainless steel and aluminium components	VFC or pit oven

Note: Most of the equipment listed in this table and Table 29.3—excepting vacuum furnaces, direct resistance and induction heating—can use either fossil fuels or electricity. Low-sulphur energy sources including natural gas, LPG (liquid petroleum gas) and electricity are preferred for high-quality work. High temperature heat treatment processes frequently use electroheat. Price and availability via the local distribution system are key factors influencing choice of fuel at a particular time and place. Fossil fuel prices will vary depending on accessibility of indigenous reserves, political factors and market forces. Electricity, being derived from other energy sources, is typically higher in price than fossil fuels but is more efficient in use because there are no flue losses.

Table 29.5 INDUCTION HARDENING PARAMETERS

Power unit	*Typical efficiency*	*Power output* (kW)	*Frequency* (kHz)	*Hardness depth* (mm)
Motor generator	0.7/0.85	15 to 300	1, 3, 4 or 10 (typical)	2 to 9
Conventional valve generator	0.5/0.6	1 to 750	450	0.5 to 2
'Aperiodic' valve generator	0.7	12 to 200	100 to 350 or 5 to 40	0.6 to 1 1 to 3
'Solid state' transistor generator	0.8/0.9	up to 12	80 to 200	0.6 to 2
'Solid state' thyristor generator	0.75/0.95	up to 80 up to 300	25 or 40 1 to 10	1 to 3 2 to 10

29.3 Steel heat treatment

29.3.1 Normalizing

Furnace or air cooling from around 950°C refines the structure and improves the toughness of low alloy steels. Figure 29.2 gives the strength and toughness of various types of low alloy steels after normalizing. Properties of nobium steels are further improved by normalization.

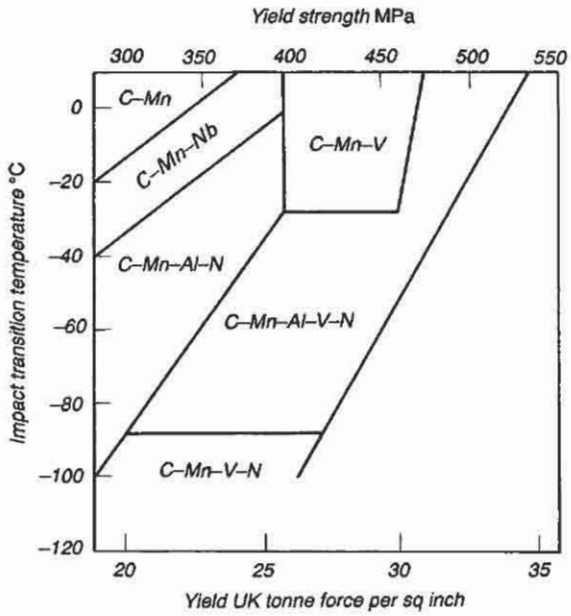


Figure 29.2 *Effect of composition on mechanical properties of normalized steels*[7]

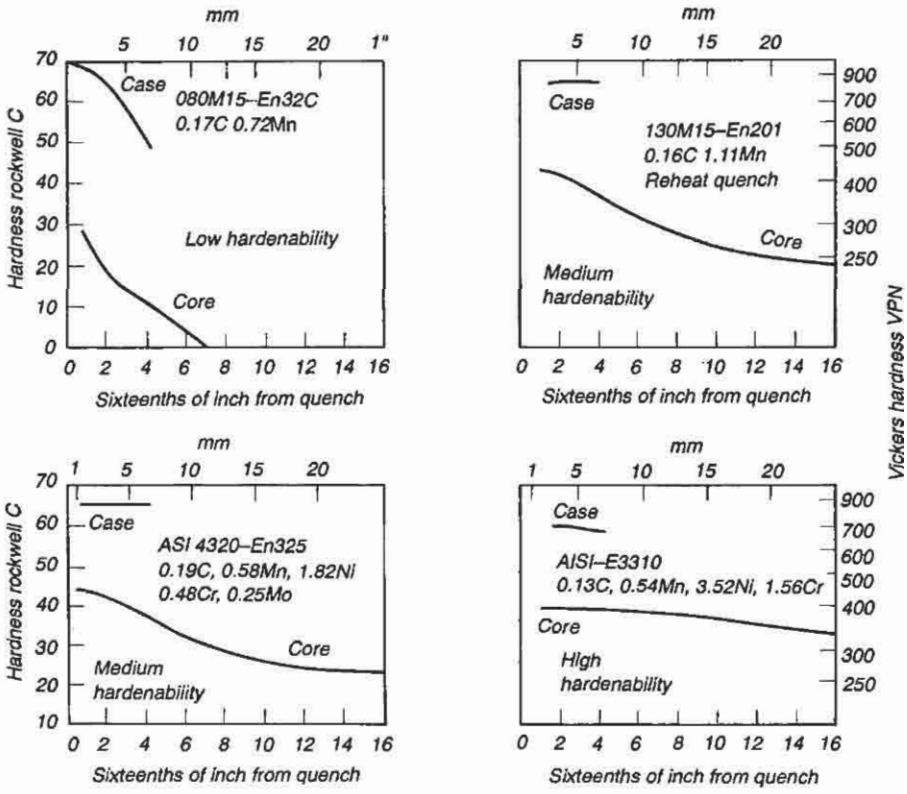


Figure 29.3 *Hardenability of case hardening steels*

29.3.2 Hardening

Rapid cooling from austenite. The rate of cooling and the composition control the structures obtained. In general steel specifications will give the recommended conditions. Guidance can be obtained from two types of diagram. This isothermal transformation diagrams (time/temperature/transformation) show the degree of transformation through time for any temperature held from the austenite treatment. These are helpful for austempering treatments but for normal hardening, continuous cooling transformation temperature diagrams (CCT) are more useful. They give transformation conditions for particular compositions when cooled from austenite in air, oil or water. Transformation starts and finishes for pearlite, bainite and martensite are shown. M. Atkins, 'An Atlas of Continuous Cooling Transformation Diagrams', British Steel Corporation, Rotherham, UK should be consulted for this information. If quench to martensite is to be followed by tempering, temperature range 290–470 should be avoided since these can produce temper brittleness. For equipment parameters in induction surface hardening see Table 29.5.

29.3.3 Case hardening

A hard outer case is provided by diffusion of carbon or nitrogen or both into the surface. For the most complete treatment four processes are involved.

(a) Diffusion of carbon into the surface between 880 and 930°C. This can be from a carbonaceous pack, from a gas or from a liquid salt, usually a cyanide. Nitrogen is usually diffused from a gas at about 500°C. For details of case depths and formulae in case hardening, see Table 29.6.
(b) Core refining. Heat treatment to refine the grain size of the core by austenitizing and quenching—see Table 29.7.
(c) Hardening. Heat treatment at a lower temperature that will austenitize the high carbon case followed by quench—see Table 29.7.
(d) Tempering. A low tempering treatment to give stress relief and reduce brittleness, usually below 200°C.

For economy, a single quench is sometimes used. After carburizing, the temperature is allowed to fall to between that of (a) and (b) followed by quench. Steels for which this is acceptable are noted in Table 29.7. Steels suitable for nitriding are listed in Table 29.8.

Surface hardening by flame or induction methods for various steels are listed in Table 29.9. For suitable induction equipment see Table 29.5. Hardness profiles of case and core for case carburizing steels of low, medium and high hardenability are given in Figure 29.3.

29.3.4 Surface treatments

As well as carbon and nitrogen, surface diffusion treatments are available using aluminium, chromium, silicon boron and zinc. These processes with their properties and applications are listed in Table 29.10. Blueing of steel parts is included.

29.3.5 High carbon steel and alloy steels

The same primary reactions apply to the heat treatment of high carbon steels as to the low carbon type, but the decarburizing reactions are of most importance. A variety of controlled atmospheres is available for industrial use and they are summarized below, the final choice being determined by the quality of product required and whether the heat treating temperature is above or below the Ac_3 point.

Above 680–700°C the atmospheres for treatment are:

1. High temperature endothermic gas, produced from rich hydrocarbon gas/air mixtures, plus hydrocarbon addition if necessary.
2. Completely burnt hydrocarbon gas, processed over hot charcoal, plus hydrocarbon if necessary.
3. Chemically purified burnt hydrocarbon gas, dry and free from carbon dioxide, plus hydrocarbon if necessary.
4. Nitrogen or nitrogen plus hydrocarbon.
5. Vacuum.

(*text continues on p29–16*)

Table 29.6 DIFFUSION PROCESSES FOR CASE-HARDENING

Process class	*Process*	*Description of process*	*Process temperature*	*Case depth*	*Advantages*	*Limitations*
Carburizing (carbon diffusion)	Pack	Parts packed within a heat-resistant box surrounded by a carburizing powder consisting of alkali carbonates, charcoal or coke tar, and molasses with a barium carbonate energizer.	~925°C	1.25 mm (5 h) 1.8 mm (10 h) 2.5 mm (20 h)	Low capital cost. Simple. Low distortion.	Labour intensive. Heat wasted.
	Liquid	Parts suspended in molten salt bath containing sodium cyanide (≤23%), barium chloride, sodium chloride and accelerators. The salt bath can be heated externally with oil gas, or electricity (submerged electrodes)	Vary according to depth required.	$d = Kt^{1/2}$ (h) Values of k 850°C = k = 0.0155 875°C = k = 0.018 900°C = k = 0.021 925°C = k = 0.025 d in inches	Simple controls can be automated. Bath heat re-usable. Can combine carburizing, refining and heat treatment.	Poisonous salts and vapours. Equipment maintenance necessary.
	Gas	A special muffle furnace allows carburizing gas mixture to pass around the workpieces. The carbon source is usually a hydrocarbon, often natural gas.	925°C max. Higher temperatures shorten furnace life and cause core grain growth.	d (in) = $\frac{31.6t^{1/2}}{10^{3722/T}}$ t = time (h) T = absolute temperature (K)	Good control. Suited to mass production. Can be combined with quenching.	High capital cost—not suited to jobbing work.

Carbonitriding	Cyaniding	Similar to liquid carburizing but 30–40% sodium cyanide. To provide nitrogen, bath must react with air. A freshly made bath is therefore aged for a few hours at 700°C before use.	870°C	Thinner cases than liquid carburizing.	Thinner but harder and more temper-resistant case than liquid carburizing. Hard wear resistant case. Longer equipment life.	Poisonous salts.
	Gas	Proportions of carbon and nitrogen may be varied. Ammonia is used to provide nitrogen	Lower than with gas carburizing. Lower temperatures increase nitrogen percentage.	Thinner cases than gas carburizing.	Hard and temper resistant case.	Similar to gas carburizing.
Nitriding	Liquid	Low temperature cyanide bath, preaged to allow cyanate formation. With low temperatures and long times the case is mostly nitride.	550°C	Thin	Hard and wear-resistant. Improved fatigue properties. Machined and hardened before casing. No distortion or grinding necessary.	Thin case. Slow process. Not suitable for heavy coarse work.
	Gas	Fully machined and heat-treated parts are nitrided in a muffle in contact with ammonia gas.	500–565°C		Similar to liquid nitriding; used for crankshafts, camshafts, gear shift forks, etc.	Case brittle and can crack or spall, if used with plain carbon steels, hence special steels necessary.

Table 29.7 CARBURIZING STEELS—LOW HARDENABILITY (see footnotes)

Steel designation	*BS 970*	*En. no.*	*C*	*Mn*	*Other*	*Refine* °C	*Harden* °C	*Tensile strength* MPa	*Elongation* %	*Impact toughness* J	*Remarks*
Carbon	045M10	32A	0.1	0.5		870–900 (1)	760–780 (W)	500	20	55	Properties sensitive to section size
	080M15	32C	0.15	0.75		870–900 (1)	760–780 (W)	500	20	55	As above
	210M15	32M	0.15	1.0	0.1–0.18 S	870–900 (1)	760–780 (W)	500	20	55	Free-cutting
Carbon–manganese	130M15	201	0.15	1.3		870–900 (1)	770–790 (W)	620	20	55	Hardenability improves core strength
	214M15	202	0.15	1.5	0.1–0.18 S	870–900 (1)	770–790 (W)	600	20	40	Free-cutting (as above)
Low chromium	—	207	0.17	0.7	0.6–0.8 Cr	—	—	600–800	—	55	Water quench for higher strength

MEDIUM HARDENABILITY

Steel designation	*BS 970*	*En. no.*	*C*	*Mn*	*Other*	*Refine* °C	*Harden* °C	*Tensile strength* MPa	*Elongation* %	*Impact toughness* J	*Remarks*
3% nickel	—	33	0.12	0.5	3 Ni	850–880 (1)	760–780 (O)	700	18	55	Good shock resistance
2% nickel–Mo	665M17	34	0.17	0.5	2 Ni 0.25 Mo	850–880 (1)	760–780 (O)	700	18	55	Good shock resistance
2% nickel–Mo (higher *C*)	665M33	35	0.23	0.5	1.7 Ni 0.25 Mo	850–880 (1)	760–780 (O)	850	15	30	Moderate shock resistance

'20' carbon low alloy	805M20	362	0.20	0.8	0.5 Ni 0.5 Cr 0.2 Mo	850–880 (1)*	780–820 (O)*	850	15	70	Low shock resistance
Low nickel–Cr–Mo	—	325	0.22	0.5	1.7 Ni 0.5 Cr 0.25 Mo	850–880 (1)*	770–800 (O)*	850	15	40	Tough, medium strength
$\frac{3}{4}$ nickel–Cr	635M15	351	0.15	0.8	0.75 Ni 0.5 Cr	850–880 (1)*	780–820 (O)*	700	18	40	Good shock resistance
'15' carbon low alloy	805M17	361	0.17	0.8	0.5 Ni 0.5 Cr 0.2 Mo	850–880 (1)*	780–820 (O)*	700	18	35	Moderate shock resistance
1% nickel–Cr	635M17	352	0.17	0.8	1.0 Ni 0.75 Cr	850–880 (1)*	780–820 (O)*	850	15	27	Moderate shock resistance

HIGH HARDENABILITY

Steel designation	*BS 970*	*En. no.*	*C*	*Mn*	*Other*	*Refine* °C	*Harden* °C	*Tensile strength* MPa	*Elongation* %	*Impact toughness* J	*Remarks*
3 nickel–Cr	655M13	36A	0.15	0.5	3.5 Ni 0.75 Cr	850–880 (1)	760–780 (O)	850	15	47	Good shock resistance
	828M13	36C	0.15	0.5	3.5 Ni 0.75 Cr	850–880 (1)	760–780 (O)	1 000	13	40	As above
5 nickel	—	37	0.16	0.45	5 Ni 0.15 Mo	850–880 (1)	750–780 (O)	620	20	68	Max toughness
4 nickel–Cr (Mo)	835M15	39B	0.15	0.4	4.0 Ni 1.2 Cr 0.2 Mo	850–880 (2)	760–780 (O)†	1 310	12	34	Heavy duty components
$1\frac{1}{4}$ nickel–Cr	815M17	353	0.17	0.75	1.25 Ni 1.0 Cr	850–880 (2)	780–820 (O)	1 000	12	27	Moderate shock resistance
$1\frac{3}{4}$ nickel–Cr–Mo	820M17	354	0.17	0.75	1.75 Ni 1.0 Cr 0.1 Mo	850–880 (2)*	780–830 (O)*	1 150	12	27	As above
2% nickel–Cr	822M17	355	0.17	0.5	2 Ni 1.5 Cr 0.2 Mo	850–880 (2)*	780–820 (O)*	1 310	12	34	Heavy duty gears, etc.

* Or single quench 810–830 (O). † Temper 200°C max. Carburize at 880–930°C. (1) = A/O/W. (2) = W/O. A = air cool. O = oil quench. W = water quench.

Table 29.8 STEELS SUITABLE FOR NITRIDING

		Composition %								Typical mechanical properties				
Steel designation	*En. no.*	*C*	*Si*	*Mn*	*Ni*	*Cr*	*Mo*	*V*	*Al*	*Section size* mm	*Yield strength* MPa	*Tensile strength* MPa	*Impact toughness* J	*Remarks*
3% chromium–molybdenum	40A	0.1 0.3	0.1 0.35	0.4 0.65	0.4 max	2.9 3.5	0.4 0.7	—	—	150	750	950	50	
3% chromium–molybdenum–vanadium	40C	0.3	0.1 0.35	0.6	0.4 max	0.2	0.1	0.1 1.3	—	60	1 100	1 300	20	Higher strength. High temperature strength. Higher hardenability.
1½ chromium–aluminium–molybdenum	41A 41B	0.25 0.45	0.1 0.45	0.65 max	0.4 max	1.4 1.8	0.10 0.25	—	0.9 1.3	60 150	850 550	1 000 850	45 50	High hardenability. Higher case hardness. High wear resistance. Corrosion resistance. 0.25–0.35% C gives core strength of 700–850 MPa. 0.35–0.45% C gives core strength of 850–1 000 MPa.
Nitralloy N	—	0.2 0.27	0.2 0.4	0.4 0.7	3.25 3.75	1.00 1.50	0.20 0.30	—	0.85 1.20	—	1 200	1 300	—	High strength.
5% Ni–2% Al	—	0.20 0.25	0.2 0.3	0.25 0.45	4.75 5.25	0.40 0.80	0.20 0.30	0.09 0.15	1.80 2.20	—	1 350	1 400	20	Very high core strength.

Table 29.9 SURFACE HARDENING BY FLAME OR INDUCTION TREATMENTS

	Basic steel composition						*Rockwell hardness* (HRc)		
Steel type	*C*	*Mn*	*Cr*	*Ni*	*Mo*	*S*	*Air* (a) *quench*	*Oil* (b) *quench*	*Water* (b) *quench*
Plain carbon	0.25–0.35	0.6	—	—	—	—	—	—	35–50
	0.4 –0.52	0.6–0.8	—	—	—	—	—	52–58	55–60
	0.55–0.75	0.6–0.8	—	—	—	—	50–60	58–62	60–63
	0.83–0.96	0.5–0.6	—	—	—	—	55–62	58–62	62–65
Free cutting	0.25–0.37	1.3–1.6	—	—	—	0.08–0.13	—	—	45–55
	0.38–0.44	1.3–1.6	—	—	—	0.08–0.13	45–55	52–57	55–62
	0.46–0.51	0.7–1.8	—	—	—	0.08–0.2	50–55	55–60	58–64
Alloy	0.38–0.48	1.6–1.9	—	—	—	—	45–55	52–57	55–62
	0.36–0.44	0.6–0.9	0.5–0.8	1.1–1.5	—	—	50–60	55–60	60–64
	0.28–0.38	0.7–0.9	0.3–1.1	—	0.15–0.25	—	—	50–55	55–60
	0.38–0.43	0.2–0.35	0.8–1.1	—	0.15–0.25	—	52–56	52–56	55–60
	0.48–0.53	0.7–1.0	0.8–1.1	—	0.15–0.25	—	58–62	58–62	62–65
	0.38–0.43	0.6–0.8	0.7–0.9	1.6–2.0	0.2 –0.3	—	55–57	53–57	60–63
	0.28–0.33	0.7–0.9	0.4–0.6	0.4–0.7	0.15–0.25	—	48–53	52–57	58–62
	0.4 –0.64	0.7–1.0	0.4–0.6	0.4–0.7	0.15–0.25	—	55–63	55–63	62–64

(a) Parts away from heated surface must be kept cool. (b) Thin sections are susceptible to cracking when oil or water quenched.

Table 29.10 DIFFUSION AND OTHER SURFACE TREATMENTS OF STEEL

Process	*Properties*	*Applications*
Aluminizing (calorizing) also for nickel and cobalt alloys. Aluminium or ferro-aluminium powder, volatile halide and ceramic heated to 815–1 200°C for 6–24 h.	Coating is about 60% Al at surface and about 150 μm. With post diffusion heat-treatment Al at surface decreases to <25% Al with decrease of thickness to <125 μm. Coating is resistant to combustion and S gases.	High temperature corrosion resistance. Chemical and petroleum processes. Engine parts.
Chromizing. Chromium powder, halide and inert aggregate heated 800–1 300°C for about 20 h in presence of hydrogen.	Surface >12% Cr and ferritic. Up to 100 μm thickness is possible. Better oxidation resistance at higher temperatures than stainless steel.	High temperature oxidation resistance.
Siliconizing. A pack of silicon carbide or ferrosilicon and circulating gas at 900–1 000°C. Silicon chloride is carrier gas.	Coating 300–750 μm. 14% Si at surface. 12% Si in bulk. Combination of corrosion and wear resistance and some oxidation resistance. Case is brittle.	Pump shafts, cylinder liners, valves and valve guides. Fittings.
Sheradizing. Diffusion of zinc to form a coating. Zn dust and sand packed around parts and heated to 300–400°C for 3–10 h. Zn vapour acts as carrier—see BS 4291.	Matt grey. Corrosion resistance proportional to thickness. Coating about 8–9% Fe. Can be painted without pretreatment. Very uniform.	Small pressings, forgings, castings, nuts, bolts, washers. Lengths of rod or tube.
Boronizing[13]. Diffusion of boron into plain carbon steel. Treatment temperature 800–1 000°C.	Very hard case. Vickers hardness $1500H_p$. Case thickness 0.05 mm (50–80 μm).	Hard surface applications.
Blueing. Used on low carbon steel. Air/steam 450–600°C. Steam must not be admitted below 350°C.	A blue mainly decorative surface is obtained.	Nuts, bolts, etc.

Below 680–700°C the atmospheres for treatment are:

1. Dry burnt hydrocarbon gas.
2. Dry burnt ammonia.
3. Cracked ammonia.
4. Nitrogen.

Processes have been developed for bright hardening in which the steel is quenched in a blast of non-oxidizing controlled atmospheres, which, if necessary, is refrigerated.

ALLOY STEELS

The nature and concentrations of the alloying elements determine the type of controlled atmosphere which will ensure freedom from oxidation or decarburization during heat treatment.

Austenitic and martensitic stainless steels, etc. If the alloying elements form oxides of low dissociation pressure, and are present in concentrations exceeding about 1%, the controlled atmosphere must be quite free from oxygen-bearing gases, and the choice is limited to cracked ammonia, dry hydrogen, or dry nitrogen/hydrogen mixtures.

Straight nickel steels These can be bright heat treated successfully in atmospheres suitable for their plain carbon steels equivalents, except that the use of a desulphurized atmosphere is advisable. For this reason all alloy steels should be degreased before treatment if surface staining is to be avoided.

Martensitic types of stainless steel Such types are treated in cracked ammonia having a controlled addition of methane or propane to prevent decarburization, and quenched in the controlled atmosphere[5] or oil.

High speed steels These are preferably treatment in salt bath furnaces, but where the nature and size of the work does not permit this a controlled atmosphere can be used[6]. The formation of an oxide skin is not objectionable, since the tools are normally surface-ground before use, and such a skin may in fact give added protection against decarburization.

TOOL STEELS AND CAST STEELS

For heat treatments of tool steels see Table 22.50. For forged and rolled steels see Table 22.44. The conditions of heat treatment for these complex steels must be obtained from individual specifications.

29.4 Cast iron treatments

29.4.1 Malleablizing

Whiteheart malleablizing—now little used—is produced by a simultaneous graphitizing and decarburizing treatment of white cast iron. The decarburizing atmosphere can be produced by a suitable atmosphere or by reaction between the air in the furnace and the carbon in the coatings. The resulting atmosphere, rich in carbon dioxide, is circulated and the carbon monoxide converted to dioxide by addition of air of steam. Batch or continuous furnaces operate at 1050°C.

For Blackheart malleablizing, decarburization is prevented by a completely neutral atmosphere such as dry nitrogen or completely burned hydrocarbon gas stripped of carbon dioxide to 0.1% and water vapour to a dew point of −40°C. Alternatively fully burned ammonia can be used—see Chapter 26–80. The carbide in the white iron changes to areas of temper carbon. The process is carried out at 1050°C (first stage) and 750–850°C (second stage).

29.4.2 Nodular cast iron or spheroidal graphite iron (SG)

The nodules of graphite are in a steel-like matrix that can be heat treated in ways similar to steel thus giving a great versatility of end products. An important development is the austempering treatment of nodular cast irons. The nodular casting—(for production see 26.9)—is first austenitized and then quenched into a temperature of between 250 and 450°C where it is held so that transformation occurs from austenite to bainite. It is then air cooled to ambient temperature. Additions of copper, nickel and molybdenum can be used to facilitate and improve the products[8,9].

29.5 Aluminium alloys

29.5.1 Annealing

For softening aluminium alloys that have been hardened by cold work:

Alloys 1080A, 1050, 1200, 5251, 5154A, 5454, 5083—360°C for 20 min.
Alloys 3103, 3105—400–425°C for 20 min.
Heat-treatable alloys that have not been heat treated—360°C ± 10°C for 1 h and cool in air.
Alloys that have been heat treated—400–425°C for 1 h and cool at 15°C/h to 300°C.
For Al–Zn–Mg alloys of the 7000 series, after cooling in air, reheat to 225°C for 2–4 h.

29.5.2 Stabilizing

To relieve internal stress. Normally heat to 250°C followed by slow cooling is adequate.

29.5.3 Hardening

Conditions for solution treatment and ageing for both cast and wrought aluminium alloys are given in Tables 29.11 and 29.12. For the alloy designation system and compositions see Chapter 22. Temper designations are given in Table 29.13.

Table 29.11 HEAT TREATMENT DATA FOR ALUMINIUM CASTING ALLOYS[10]

Material designation and temper	*Alloy type*	*Solution treatment*			*Precipitation treatment*	
		Temperature °C	*Time*[1] h	*Quench*[2] *medium*	*Temperature* °C	*Time*[3] h
BS 1490						
LM 4 –TF	Al Si5 Cu3	505–520	6–16	Hot water	150–170	6–18
LM 9 –TE	Al Si12 Mg	—	—	—	150–170	16
–TF		520–535	2–8	Water	150–170	16
LM 10–TB	Al Mg10	425–435	8	Oil at 160°C max[4]	—	—
LM 13–TE	Al Si11 Mg Cu	—	—	—	160–180	4–16†
–TF		515–525	8	Hot water	160–180	4–16
–TF7		515–525	8	Hot water	200–250	4–16
LM 16–TB	Al Si5 Cu1 Mg	520–530	12	Hot water	—	—
–TF		520–530	12	Hot water	160–179	8–10
LM 22–TB	Al Si6 Cu3 Mn	515–530	6–9	Hot water	—	—
LM 25–TB7	Al Si7 Mg	525–545	4–12	Hot water	250	2–4
–TE		—	—	—	155–175	8–12
–TF		525–545	4–12	Hot water	155–175	8–12
LM 26–TE	Al Si9 Cu3 Mg	—	—	—	200–210	7–9
LM 28–TE	Al Si19 Cu Mg Ni	—	—	—	185	†
–TF		495–505	4	Air blast	185	8
LM 29–TE	Al Si23 Cu Mg Ni	—	—	—	185	†
–TF		495–505	4	Air blast	185	8
LM 30–TS	Al Si17 Cu4 Mg	—	—	—	175–225	8
BS 'L' series						
4L 35	Al Cu4 Ni2 Mg2	500–520	6	Boiling water	95–110 or room temperature	2 5 days
3L 51	Al Si2 Cu Ni Fe Mg	—	—	—	150–175	8–24
3L 52	Al Cu2 Ni Si Fe Mg	520–540	4	Water at 30–100°C	150–180 or 195–205	8–24 2–5
4L 53	Al Mg10	425–435	8	Oil at 160°C max[4]	—	—
3L 78	Al Si4 Cu1	520–530	12	Hot water	160–170	8–10
2L 91	Al Cu4	525–545	12–16	Hot water	120–140	1–2
2L 92	Al Cu4	525–545	12–16	Hot water	120–170	12–14
L 99	Al Si6	535–545	12	Hot water	150–160	4
L 119	Al Cu5 Ni1	542±5	5	Boiling water or oil at 80°C	215±5	12–16
L 154	Al Cu4 Si1	510±5	16	Water (50–70°C)	—	30 days
L 155	Al Cu4 Si1	510±5	16	Water (50–70°C)	140±10	16
DTD specifications						
722B	Al Si5				165±10	8–12
727B	Al Si5	540±5	4–12	Water (80–100°C) or oil	130±10	1–2
735B	Al Si5	540±5	4–12	Water (80–100°C)	165±10	8–12
5008B	Al Zn5 Mg	—	—	—	180±5	10
5018A	Al Mg7 Zn	430±5	8	Oil >160°C >1 h then oil at room temperature, or air	—	—
or		440±5	8			
then		495±5	8	Boiling water	—	—

[1] Single figures are minimum times at temperature for average castings and may have to be increased for particular castings.
[2] Hot water means water at 70–80°C unless otherwise stated.
[3] The exact number of hours depends on the mechanical properties required.
[4] The castings may be allowed to cool to 385–395°C in the furnace before quenching. The castings shall be allowed to stay in the oil for not more than 1 h and may then be quenched in water or cooled in air.
† The duration of the treatment shall be such as will produce the specified Brinell hardness in the castings.
* For temper designation see Table 29.13.

Table 29.12 TYPICAL HEAT TREATMENT DATA FOR WROUGHT ALUMINIUM ALLOYS[10]
Times and temperatures within the limits shown. Some specifications give tighter limits

Material designation	*Alloy type*	*Temper*‡	*Solution treatment*		*Ageing temperature* °C	*Time at temperature* h
			Temperature °C	*Quench medium*†		
2011	Al Cu5.5 Pb Bi	T 3 (TD)	510±5	Water	Room	48
		T 6 (TF)	510±5	Water	155–165	12
2014A	Al Cu4 Si Mg	T 3 (TD)	505±5	Water	Room	48
		T 4 (TB)	505±5	Water	Room	48
		T 6 (TF)	505±5	Water	155–190	5–20
		T 651	505±5	Water	155–190	5–20
2024	Al Cu4 Mg1	T 351	495±5	Water	Room	48
		T 4 (TB)	495±5	Water	Room	48
		T 42	495±5	Water	Room	48
2031	Al Cu2 Ni1 Mg Fe Si	T 4 (TB)	525±10	Water or oil	155–205	2–20
2117	Al Cu2 Mg	T 4 (TB)	495±5	Water	Room	96
2618A	Al Cu2 Mg1.5 Fe1 Ni1	T 6 (TF)	530±5	Water	160–200	16–24
6061	Al Mg1 Si Cu	T 4 (TB)	525±15	Water	Room	—
		T 6 (TF)	525±15	Water	165–195	3–12
6063	Al Mg Si	T 4 (TB)	525±5	Water	Room	—
		T 5 (TE)	—	—	160–180	5–15
		T 6 (TF)	525±5	Water	160–180	5–15
6082	Al Si1 Mg Mn	T 4 (TB)	530±10	Water	Room	120
		T 6 (TF)	530±10	Water	175–185	7–12
		T 651	525±15	Water	165–195	3–12
6101A	Al Mg Si	T 4 (TB)	525±5	Water	Room	120
		T 6 (TF)	525±5	Water	170±10	
6463	Al Mg Si	T 4 (TB)	525±5	Water	Room	120
		T 6 (TF)	525±5	Water	170±10	5–15
7010	Al Zn6 Mg2 Cu2	T 351	475±10	Water	—	—
		T 7651	475±10	Water	172±3*	6–15
				or	120±3	24
				followed by	172±3	6–15
		T 73651	465±10	Water	172±3*	10–24
7014	Al Zn5.5 Mg2 Cu Mn	T 6 (TF)	460±10	Water 85°C or oil	135±5	12
		T 6510	460±10	Water or oil	135±5	12
7075	Al Zn6 Mg Cu	T 6 (TF)	460±10	Water	135±5	12
		T 651	460±10	Water	135±5	12
		T 73	465±5	Water (60–80°C)	110±5	6–24
				or	120±5	20–30
				followed by	177±5	6–10
		T 7351	465±5	Water	110±5	6–24
				followed by	177±5	5–12
		T 7352	465±5	Water 70°C	110±5	6–24
				or	120±5	20–30
				followed by	177±5	6–10

* Heating to temperature at not more than 20°C/h.
† Water below 40°C unless otherwise stated.
‡ For temper designations see Table 29.13.

Table 29.13 ALUMINIUM ALLOY TEMPER DESIGNATIONS

Symbol	*Condition*
Casting alloys BS 1490	
M	As cast
TB	Solution treated and naturally aged
TB7	Solution treated and stabilized
TE	Artificially aged
TF	Solution treated and artificially aged
TF7	Solution treated, artificially aged and stabilized
TS	Thermally stress relieved

Table 29.13 ALUMINIUM ALLOY TEMPER DESIGNATIONS – *continued*

Symbol	*Condition*
BSEN515	
T 1	Cooled from elevated temperature shaping process and naturally aged to stable condition
T 2	As T 1 but cold worked after cooling from elevated temperature
T 3 (TD)	Solution treated, cold worked and naturally aged to stable condition
T 4 (TB)	Solution treated and naturally aged to stable condition
T 5 (TF)	Cooled from elevated temperature shaping process and artificially aged
T 6	Solution treated and artificially aged
T 7	Solution treated and stabilized (averaged)
T 8 (TH)	Solution treated, cold worked and then artificially aged
T 9	Solution treated, artificially aged and then cold worked
T 10	Cooled from elevated temperature shaping process, artificially aged and then cold worked

29.6 Copper and copper base alloys

29.6.1 Environments for copper base heat treatments

Stream and carbon dioxide are virtually inactive to copper and both are used on an industrial scale. The former has the disadvantage of giving rise to water staining, while the latter is less economical. Burnt hydrocarbon gas is used extensively for bright annealing copper, but the metal is very susceptible to staining by hydrogen sulphide. Organic sulphur and sulphur dioxide do not attack copper but may be converted to hydrogen sulphide so that complete desulphurization of the controlled atmosphere is advisable. Sulphur compounds are much reduced if the gas is fully burnt rather than partially burnt. Cracked and burnt ammonia are suitable for copper annealing and are sulphur free, but the former is little used for economic reasons.

Tough pitch copper contains oxygen and hydrogen in the controlled atmosphere must be less than 1%. Burnt ammonia or burnt hydrocarbon gas can be used; however, embrittlement can occur due to reaction of steam with iron in the furnace producing hydrogen. An open flame furnace in which the preferably desulphurized gas is fully burnt can be used in bright annealing.

Copper-tin and copper-nickel alloys can be bright annealed as above but desulphurization must be absolutely complete. For alloys containing more readily oxidized elements, the range of suitable atmospheres is restricted to ammonia or dry burnt ammonia.

Copper-zinc alloys. A successful industrial process[11] has been developed for the full annealing of brass with zinc content up to at least 37%. CO, CO_2 and water vapour must be minimal and the atmosphere should contain some hydrogen. Typical composition is 25% H/N with max O_2 1 vpm, CO_2 20 vpm and de point -70°C. Zinc has a considerable vapour pressure at annealing temperatures and this may affect the colour and surface finish. Temperatures and soak times should be chosen with care. Where finish is less critical, 'flash' annealing may be applied to light gauge material with good results where rapid heating and cooling may be applied. Commercial annealing is often carried out in the cheaper types of controlled atmospheres which produce a light oxide film sufficient to restrict excessive zinc loss.

Gilding metal contains low zinc concentration and can be bright annealed readily in atmospheres used for the annealing of copper, especially when in the form of coiled strip.

29.6.2 Temperatures for annealing and stress relief

These are are set out in Table 29.14. For more details on copper base alloys reference should be made to Copper Development Association data sheets.

Table 29.14 ANNEALING AND STRESS RELIEVING OF COPPERS AND BRASSES†

ISO alloy designation	*Annealing range* (°C)	*Stress relieving range* (°C)
Coppers		
Cu-ETP and Cu-FRH	200–650*	150–200*
Cu-FRTP	225–650*	175–225*
Cu-OF	200–650	170–200
Cu-DLP	225–600	175–225
Cu-DHP	250–650	200–250
Cu-DPA	375–650	225–275
Cu-LSTP and Cu-OFS	350–650*	225–275*
Cu S	400–650	225–275
Cu Te	425–650*	225–275*
Cu Cd3 and Cu Cd Sn	500–700	250–350
Cu Si3 Mn1	475–700	250–380
Brasses		
Cu Zn5–20	425–600	200–300
Cu Zn28–30	450–680	250–350
Cu Zn33–40	450–650	250–350
Cu Zn9 Pb2	425–600	200–320
Cu Zn34 Pb2	450–620	250–350
Cu Zn34–40 Pb1–3	450–650	250–350
Cu Zn43 Pb2	425–550	250–350
Cu Zn20 Al2	450–650	250–350
Cu Zn28 Sn1	450–650	250–350
Cu Zn38 Sn1	450–600	225–325
Cu Ni10–12 Zn24–27	600–750	250–350
Cu Ni15–18 Zn21–20	625–775	250–350
Cu Ni18 Zn27	650–800	250–350
Cu Ni10 Zn42 Pb2	600–700	300–400
Cu Ni18 Zn19 Pb1	625–775	300–400

* Embrittlement will occur if heated in atmosphere containing excess of hydrogen.
† For more details see Copper Development Association data TN 26 and 27.

29.7 Magnesium alloys

29.7.1 Safety requirements[1,2]

A potential fire hazard exists in the heat treatment of magnesium alloys. Overheating and direct access to radiation from heating elements must be avoided and the furnace must be provided with a safety cutout which will turn off heating and blowers if the temperature goes more than 6°C above the maximum permitted. In a gastight furnace a magnesium fire can be extinguished by introducing boron trifluoride gas through a small opening in the closed furnace after the blowers have been shut down.

29.7.2 Environment

For temperatures over 400°C, surface oxidation takes place in air. This can be suppressed by addition of sufficient sulphur dioxide, carbon dioxide or other suitable oxidation inhibitor.

In the case of castings to MEL ZE63A and related specifications, solution treatment should be carried out in an atmosphere of hydrogen and quenching of castings from solution treatment temperature of MEL QE22 is to be done in hot water.

If microscopic examination reveals eutectic melting or high temperature oxidation, rectification cannot be achieved by reheat-treatment. Quench from solution treatment should be rapid, either forced air or water quench. From ageing treatment, air cool.

29.7.3 Conditions for heat treatment of magnesium alloy castings

These are shown in Table 19.15 and for some wrought magnesium alloys in Table 19.16. Stress relief treatments are given in Table 19.17.

Table 29.15 HEAT TREATMENT OF MAGNESIUM CASTING ALLOYS

Specifications	*Composition*	*Solution treatment*		*Ageing*	
		Temperature (°C)	*Time* (h) *quench*	*Temperature* (°C)	*Time* (h) *quench*
MEL ZRE1 BS 2L126 BS 2970 MAG 6 ASTM EZ33A UNS M12330	Zn2.5 Zr0.6 RE3.5	—	—	250	16 AC
MEL RZ5 BS 2L128 BS 2970 MAG 5 ASTM ZE41A UNS M16410	Zn4.2 Zr0.7 RE1.3	—	— +	330 170–180	2 AC 10–16 AC
MEL ZE63A DTD 5045 ASTM ZE63A	Zn5.8 Zr0.7 RE2.5	480*	10–72 WQ	140	48 AC
MELZT1 DTD 5005A BS 2970 MAG 8 ASTM HZ32A	Zn2.2 Zr0.7 Th3.0	—	—	315	16 AC
MEL TZ6 DTD 5015A BS 2970 MAG 9 ASTM ZH62A UNS M16620	Zn5.5 Zr0.7 Th1.8	—	— +	330 170–180	2 AC 10–16 AC
MEL EQ21A	Ag1.5 Zr0.7 Cu0.07 Nd(RE)2.0	520	8 WQ	200	12–16 AC
MEL MSR-B DTD 5035A	Ag2.5 Zr0.6 Nd(RE)2.5	520–530	4–8 WQ	200	8–16 AC
MEL QE22 (MSR) DTD 5055 ASTM QE22A UNS M18220	Ag2.5 Zr0.6 Nd(RE)2.0	520–530	4–8 WQ Hot WQ	200	8–16 AC
MEL A8 BS 3L122 BS 2970 MAG1 ASTM AZ81A UNS M11818	Al8.0 Zn0.5 Mn0.3	380–390 410–420	8 AC 16 AC	—	—
MEL AZ91 (ST) BS 3L124 BS 2970 MAG 3	Al9.0 Zn0.5 Mn0.3 Be0.0015	380–390 410–420	8 AC 16 AC	—	—
ASTM AZ91C (ST&PT) UNS M11914	Al9.0 Zn0.5 Mn0.3 Be0.0015	380–390 410–420	8 AC 16 AC	200	10 AC
MEL MAG 7 (ST) BS 2970 MAG 7	Al7.5/9.5 Zn0.3/1.5 Mn0.15	380–390 410–420	8 AC 16 AC	—	—
MEL MAG 7 (ST&PT)	Al7.5/9.5 Zn0.3/1.5 Mn0.15	380–390 410–420	8 AC 16 AC	200	10 AC

* In hydrogen. Max 490°C.

Table 29.16 HEAT TREATMENT OF MAGNESIUM WROUGHT ALLOYS

Specifications	*Composition*	*Form*	*Solution treatment*		*Ageing*	
			Temperature (°C)	*Time* (h) *quench*	*Temperature* (°C)	*Time* (h) *quench*
MEL AZ80 ASTM AZ80A	Al8.5 Zn0.5 Mn0.12	Ex	—	—	177	16 AC
UNS M11800		F	400	2–4 WQ	177	16–24 AC
ASTM HM31A UNS 13310	Th2.5–4.0 Zn0.3 Zr0.4–1.0	Ex	—	—	232	16 AC
ASTM 60A UNS 16600	Zn5.5	F T6 F T4 F T5	500 500 —	2 WQ 2 WQ —	150 — 150	24 AC — 24 AC

Notes: Ex—extrusions, F—forgings, T4—solution treated, T5—cooled and artificially aged, T6—solution treated and artificially aged, AC—air cool, WQ—water quench.

Table 29.17 STRESS RELIEF TREATMENTS FOR WROUGHT MAGNESIUM ALLOYS

Specifications	*Composition*	*Form*	*Temperature* (°C)	*Time* (min)
MEL AZM ASTM AZ61A UNS 11610	Al6.0 Zn1.0 Mn0.3	Ex&F SH SA	260 204 343	15 60 120
MEL AZ80 ASTM AZ80 UNS 11811	Al8.5 Zn0.5 Mn0.12min	Ex&F Ex&F*	260 204	15 60
MEL AZ31 ASTM AZ31B UNS 11311	Al3.0 Zn1.0 Mn0.3	Ex&F SH SA	260 149 343	15 60 120

Notes: Ex—extrusions, F—forgings, SH—sheet hard rolled, SA—sheet annealed, *—cooled and artificially aged.

29.8 Nickel and cobalt alloys

For bright annealing of nickel alloys, ammonia, burnt ammonia or hydrogen atmospheres can be used but the dew point should be below −50°C. All traces of sulphur gases should be excluded from atmospheres in which nickel alloys are heat treated.

The heat treatments of some nickel alloys are given in Table 29.18 and some cobalt alloys in Table 29.19. These alloys are normally used by name and therefore these tables do not give the alloy type. The UNS number (see Chapter 1) is given when available.

Table 29.18 HEAT TREATMENT OF NICKEL ALLOYS

		Annealing		*Stress relief*		*Solution treatment*		*Ageing*	
Alloy	*UNS*	*Temp.* (°C)	*Time* (hs)	*Temp.* (°C)	*Time* (hs)	*Temp.* (°C)	*Time* (h)	*Temp.* (°C)	*Time* (h)
Astroloy	—	1135	4	f	f	1175	4 AC	845	24 AC
						1080	4 AC	760	16 AC
Hastelloy B	N10001	1175	1	f	f	1175	0.5 SQ	AS	
Hastelloy B2	N10665					1065	0.5 WQ	—	
Hastelloy C4	N06455	1215	1	f	f	1065	0.5 WQ	—	
Hastelloy C276	N10226					1120	0.5 WQ	—	

Notes: FC = furnace cool, AC = air cool, h = hours, hs = hours/inch of section, WQ = water quench, AS = ageing during service, f = use full anneal, SQ = quench below 540°C rapidly enough to prevent precipitation.

Table 29.18 HEAT TREATMENT OF NICKEL ALLOYS—*continued*

		Annealing		*Stress relief*		*Solution treatment*		*Ageing*	
Alloy	*UNS*	*Temp.* (°C)	*Time* (hs)	*Temp.* (°C)	*Time* (hs)	*Temp.* (°C)	*Time* (h)	*Temp.* (°C)	*Time* (h)
Hastelloy N	N10003					1 175	0.5 WQ	—	
Hastelloy S	—					1 065	0.5 WQ	—	
Hastelloy C	—					1 220	1 SQ	AS	
Hastelloy W	N10004	1 175	1	f	f	1 175	1 SQ	AS	
Hastelloy X	N06002	1 175	1	f	f	1 175	1 SQ	—	
Inconel 901	—	1 095	2	f	f	1 095	2 WQ	790	2 AC
Inconel 600	N06600	1 010	0.25	900	1	1 120	2 AC	—	
Inconel 601	N06601	980		f		1 150	1 AC	—	
Inconel 625	N06625	980	1	870	1	1 150	2 SQ	—	
Inconel 617	—					1 175	2 SQ	—	
Inconel 706	—					925–1 010		845	3 AC
								720	8 FC
								620	8 AC
Inconel 718	N07718	955	1		f	980	1 AC	720	8 FC
								620	8 AC
Inconel X750	N07750	1 035	0.5	880		855	24 AC	705	20 AC
AMS 5667						1 150	2 AC	845	24 AC
AMS 5668									
Nimonic 80A	N07080	1 080	2	f	f	1 080	8 AC	705	16 AC
Nimonic 90	N07090	1 080	2	f	f	1 080	8 AC	705	16 AC
Rene 41	N07041	1 080	2	f	f	1 065	0.5 AC	760	16 AC
Unimet 500	N07500	1 080	4	f	f	1 080	4 AC	845	24 AC
Unimet 700	—	1 135	4	f	f	1 175	4 AC	845	24 AC
						1 080	4 AC	760	16 AC
Waspalloy	N07001	1 010	4	f	f	1 080	4 AC	845	24 AC
								760	16 AC

Notes: FC = furnace cool, AC = air cool, h = hours, hs = hours/inch of section, WQ = water quench, AS = ageing during service, f = use full anneal, SQ = quench below 540°C rapidly enough to prevent precipitation.

Table 29.19 HEAT TREATMENT OF COBALT ALLOYS

		Annealing		*Stress relief*	*Solution treatment*		*Ageing*	
Alloy	*UNS*	*Temp.* (°C)	*Time* (hs)	*Temp.* (°C) *Time* (hs)	*Temp.* (°C)	*Time* (h)	*Temp.* (°C)	*Time* (h)
Hayes 25	R30605	1 230	1	f	1 230	1 RAC	AS	
L-605								
Hayes 188	R30188				1 175	0.5 RAC	—	
Hayes 566	—				1 175	0.5 RAC	—	
S816	R30816	1 205	1	f	1 175	1 SQ	760	12 AC
Stellite 6B	—				1 230	1 AC	—	

Notes: RAC = rapid air cool, AC = air cool, h = hours, hs = hours/inch of section, AS = ageing during service, f = use full anneal, SQ = quench below 540°C rapidly enough to prevent precipitation.

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30 Laser metalworking

30.1 Introduction

Laser radiation, in contrast to that from black body sources, can offer a high degree of spatial coherence. This means that it can transmit as a well-directed, often near-parallel beam which may then be focused to spot diameters comparable with the wavelength of the radiation. Illustratively, beams of kilowatt power may be transmitted through air and then focused to intensities in excess of $10^6\,W\,cm^{-2}$ which, when applied appropriately to a metal workpiece, permit the carrying out of processes such as drilling, cutting and welding.

Importantly, because these processes are carried out at intensities much greater than those of conventional sources, heating is localized and there is usually a related reduction in phenomena such as distortion, shrinkage and heat-affected-zones. As a result the need for post-process machining may be eliminated so that components go into use directly; this can, of course, be an important factor in the overall economics. Thus the unique combination of high focused power density, coupled with the facility for beam delivery and flexible use at ambient pressure, has resulted in a continuing growth in industrial applications in laser metal working.

30.2 Lasers

30.2.1 Basic principles

The three essential components of a laser are the laser medium, the excitation source and the optical resonator (Figure 30.1). The excitation source drives the atoms, ions or molecules of the laser medium to a situation where there is an excess of those at high energy level over those at a low level. This inversion of the normal thermodynamic population distribution leads to laser action:

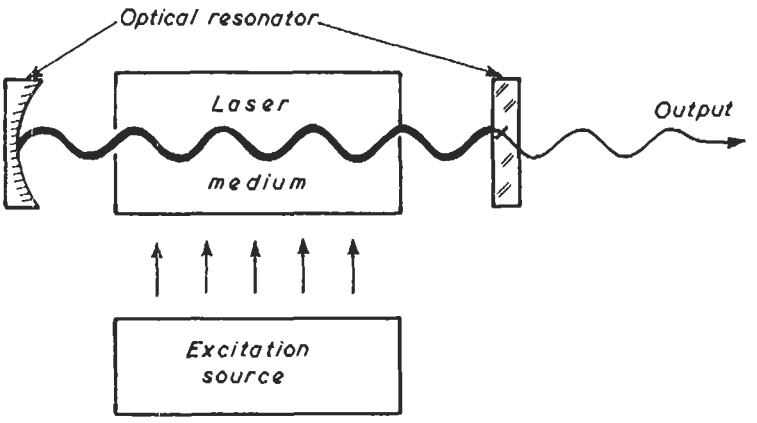


Figure 30.1 *Essentials of a laser*

an excited member of the medium undergoing a transition from high to low energy will emit a photon, which in turn stimulates further emission, perfectly in phase, and at the same wavelength, from the other excited members of the medium. The radiation is thus rapidly amplified; the role of the optical resonator is to direct and control the radiation by allowing an appropriate fraction to be bled off as a near-parallel beam while the remainder is circulated within the cavity to maintain laser action. The output is monochromatic, usually with high spatial and temporal coherence. At present, metal working applications involve use of predominantly two laser types, carbon dioxide (CO_2) and neodymium YAG (Nd:YAG). The salient features of the two types are summarized in Table 30.1 and they are discussed in turn below.

30.2.2 CO_2 lasers

In these lasers, the laser action results from electric discharge excitation of a low pressure gas mixture containing carbon dioxide. The beam is invisible, having a wavelength λ lying in a far intrared at $\lambda = 10.6\,\mu$m. Industrial units are available with powers up to 10 kW and above. Whilst early CO_2 lasers were almost exclusively of continuous wave (CW) operation, many low to medium power units now offer kilohertz pulsing capabilities. Since the pulse power may be ten times the average power, such operation can give better coupling of the beam into reflective metal surfaces. Additionally, pulsing may permit improved control of energy delivery to the work and this can be important, for example in the processing of thin sections. Current trends in laser development have resulted in the use of radio frequency (RF) excitation of the discharge in some designs. In general, research and development continues on the building of ever higher power CO_2 lasers. Motivated by the promise of increased single-pass weld penetration, work is underway on the design of improved 25 kW units.

30.2.3 Nd:YAG lasers

Here the laser action results from the excitation of a solid rod of yttrium aluminium garnet, doped with neodymium, by intense white light from a lamp which may be pulsed or continuous. As in the CO_2 laser, the beam is invisible but here it is in the near infrared at $\lambda = 1.06\,\mu$m. Currently, most metal-working Nd:YAG lasers have average powers in the region of several hundred watts, and have an output which is pulsed. A pulse may deliver tens of joules of optical energy in a millisecond, so that power at the workpiece may be tens of kilowatts. As a result, Nd:YAG lasers are well suited to drilling. They are also used very successfully for cutting and, with less intense pulses, for welding and surface treatment. Present trends in laser development have led to the availability of powers of 1 kW and above, and to the increasing appearance of cw units. Replacement of rod geometry by that of slabs is claimed to ease cooling problems, reduce distortion and improve beam quality.

Because high beam power is more readily achievable, and available, in CO_2 lasers than in Nd:YAG lasers, the latter have been mainly associated with fine-scale applications whereas CO_2 lasers tend to be used for larger-scale application. However, with Nd:YAG units now offering beam powers of 1 kW and above, there is a greater overlap of capabilities in the cutting and welding of metal thicknesses which represent a significant part of engineering production.

30.2.4 Resonators

The beam–metal interaction process is strongly affected by the intensity distribution of the beam, which in turn is influenced by the design of the optical resonator (or cavity). These fall into two categories: stable and unstable. The terms refer to a mathematical description of the resonator which will not be attempted here. Figure 30.2 compares practical realizations of a stable and unstable cavity.

The stable cavity is particularly suited to long lasers of low aperture, and in a well-designed system only the lowest-order mode (TEM_{00}) will be sustained, yielding an output beam which has a Gaussian radial intensity distribution

$$I = I_0 e^{-r/\omega}$$

where I = intensity (as a function of radius), I_0 = on-axis intensity, r = radial position, ω = 'spot radius' at which the intensity falls to 1/e of axial value.

This distribution has a strong central peak, steep sides and low wings; it is obtained also in the beam spot after focusing and it appears to correspond to excellent metal penetration capabilities.

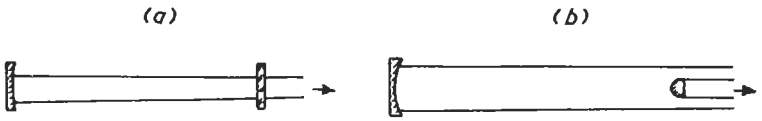


Figure 30.2 *(a) Stable and (b) unstable cavity resonators*

On the other hand, a stable cavity can be arranged to sustain higher-order transverse modes so that instead of there being a lone spike of high intensity, additional rings appear around it (the TEM_{01}* mode gives the first ring alone). The redistribution of power results in a broader, flatter distribution in both the output beam and the focused spot. Although such multimode beams do not appear to be particularly well suited to creation of deep, narrow cuts and welds, they may be preferable for surface treatment processes requiring an extended uniform distribution.

If the laser gain medium tends towards a geometry of short length and high aperture, an unstable resonator must normally be used to ensure good mode control and focusability. As seen in Figure 30.2(b), the output beam is annular. This distribution (which should not be confused with the much less focusable TEM_{01}*) yields, after focusing, an Airey pattern distribution which is strongly peaked on axis but with some power in concentric rings. For lasers with high gain where the central hole in the annulus is small (high magnification cavity), the power after focusing is predominantly in the central spike, giving generally very acceptable cutting and welding performance. One special merit of the unstable resonator is that the out-of-focus annular distribution is well suited to metal surface treatment operations.

30.2.5 Beam delivery

The beam emerging from the laser is only near-parallel; if it is transmitted a significant distance before use, the growth in diameter may need to be taken into account in choosing the diameter of beam lines and focus units. Consider the case of a laser having TEM_{01} mode: the beam envelope

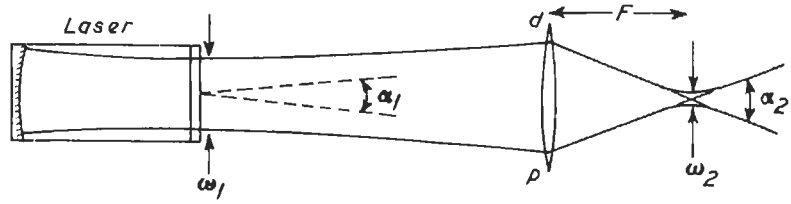


Figure 30.3 *Laser beam focusing*

typically consists of a waist region (diameter ω_1, left-hand side of Figure 30.3) and a region bounded by straight lines of divergence α. Then

$$\alpha_1 = \frac{4}{\pi}\frac{\lambda}{\omega_1}$$

It is seen at once that for a given beam diameter, a short wavelength laser will have less divergence than one with long λ; for a given wavelength, a large diameter beam will have less divergence than one with small diameter. If the beam is now focused on to the workpiece by a lens of focal length F (right-hand side of Figure 30.3), the near field distribution at waist ω_1 is transformed to the far field distribution at waist ω_2. Further lenses can effect further transformations, the product

$$\omega_1\alpha_1 = \omega_2\alpha_2 = \omega_n\alpha_n$$

being a constant. It can be shown that the diameter of the focused spot is

$$\omega_2 \approx \frac{4\lambda}{\pi\alpha_2} \approx \frac{4}{\pi}\lambda\frac{F}{d} \approx \frac{4}{\pi}\lambda\ (f/\text{number})$$

where d is the diameter of the beam at the lens and the lens f/number $= F/d$. If depth of focus is

defined by a distance z from focus at which the axial power density has fallen by 10% from that at focus, then

$$z \approx \pm \frac{\pi}{12} \frac{\omega_2^2}{\lambda}$$

It is seen that short wavelength gives smaller spots and greater depth of focus than long, and that short focal length lenses will give smaller spots and more shallow depth of focus than long (provided that aberrations do not dominate). In practice, $f/3$ focusing might be chosen for high speed cutting of thin sheet where depth of focus is less important, whilst $f/10$ to $f/15$ focusing might be chosen for high power welding of 15-mm thick steel where a broad depth of focus is desirable.

As an alternative to beam transmission through air, optical fibres may be used for Nd:YAG lasers; quartz fibres offer good transmission at 1.06 μm and are capable of operation with kilowatt power levels. On the other hand, suitable low-loss optical materials capable of transmitting high power 10.6 μm radiation have not yet been developed. Nevertheless, flexible beam delivery systems for CO_2 lasers do exist based on line of sight transmission between suitably articulated mirrors.

TABLE 30.1 CHARACTERISTICS OF Nd:YAG AND CO_2 LASERS

	Nd:YAG	CO_2
Relevant energy levels	Electron orbits of neodymium ion in host lattice of yttrium aluminium garnet ($Y_3Al_5O_{12}$)	Stretching of CO_2 molecule
Laser wavelength	1.06 μm	10.6 μm
Laser medium	Solid rod of Nd:YAG	Gaseous CO_2 (usually with He and N_2, total pressure ~50 mbar)
Excitation	White ligbt excitation from flash tubes beside rod	Collisional excitation by electrons of glow discharge operated in gas mixture. power supply may be DC or AC up to RF
Waste heat removal	Water cool rod	(i) Operate discharge in glass tubes and water cool tube walls (ii) Blow gas through discharge and then cool in heat exchanger
Typical operating conditions, including pulsing	cw ⩽1 kW pulse lamp 20 Hz, 20 j per pulse Q switch 20 kHz 150 W mean	⩽5 kW cw and RF, pulsable up to several kHz. 10–20 kW mainly cw
Overall efficiency	⩽4%	⩽10%
Resonator	Stable or unstable	Stable or unstable
Mirrors	Dielectric	Metal
Lenses	Glass, as for visible light	e.g. ZnSe, KCl
Part of eye most at risk from accidental exposure	Retina	Cornea

30.3 Processing considerations

30.3.1 Role of intensity

Each of the categories of laser metal-processing (drilling, welding, surface cladding, transformation hardening) can be characterized approximately by the beam intensity (beam power divided by beam spot-area) applied to the work, and by illustrative metal surface temperatures. In drilling steel for example it is desirable to use very high intensity ($\geqslant 10^7$ W/cm^2) so that super-heating occurs (temperatures >3000°C), leading to explosive ejection of liquid and solid material, thereby yielding very efficient machining. In deep penetration welding, where the creation of the welding capillary involves melting and carefully controlled vaporization, intensities of 10^6 W/cm^2 and a little above are normally employed. Surface cladding requires good melting with negligible vaporization, i.e. t <3000°C and intensities of 10^4–10^5 W/cm^2 are used. In transformation hardening, surface melting must not occur, i.e. temperature must be held below 1500°C for steel, and typical intensities are $\geqslant 10^3$ w/cm^2.

30.3.2 Beam coupling

Clean, smooth metal surfaces are good reflectors of infrared radiation although they are more absorbing at the Nd:YAG wavelength than that of the CO_2 laser. Indeed, 'perfect' metal surfaces may have reflectances in the range 60–90%. However, reflectivity decreases with increasing temperature, presence of oxides, onset of surface melting, and capillary formation. The result is that in most practical applications even the CO_2 laser beam is efficiently coupled to the metal.

In drilling, cutting and welding, the focus intensity is sufficiently high (particularly in the case of pulsed beams) to initiate melting, surface disruption and capillary formation which yields efficient beam trapping. In CO_2 laser welding, plasma formation associated with the capillary also contributes by absorbing beam energy and redistributing it to the metal by conduction. In cutting, the assist gas jet keeps the cut slot (kerf) relatively clear so that the beam couples directly to the kerf leading edge and sides. It is found that better coupling occurs in CO_2 laser cutting for a plane polarized beam having the electric vector lying along the cut (Brewster effect). The overall result is that the machining processes exhibit a very highly efficient utilization of the beam. However, CO_2 lasers are not suited to the processing of gold, and they require good beam quality for processing of copper and aluminium.

Surface melting, cladding and alloying can be carried out with high efficiency using Nd:YAG lasers, and with acceptable efficiency using CO_2. Because there is no strong capillary feature in these processes, some CO_2 beam reflection does occur. However, when powders are being fused into metal surfaces, their delivery into the interaction region can provide a surface with good absorptivity, and typical overall beam utilization efficiencies may be better than 30%.

The implementation of efficient transformation hardening by CO_2 laser relies on the presence of an absorbing coating. This may be an oxide layer grown during processing, but it is more normal to employ a pre-applied thin layer of colloidal graphite. Such coatings can present greater than 80% absorptivity. As in the case of cutting, the Brewster effect may be used to give better coupling when the beam has to be inclined to the surface: the beam should be plane polarized with the electric vector lying in the plane of incidence–reflection.

30.3.3 Processing depths and rates

Cutting and welding

In these processes, prediction from first principles of the depth of penetration achievable with a given laser beam is at present not a practical proposition. This is a consequence of the complexity of the beam interaction processes occurring in the kerf and keyhole. Nevertheless, a simple energy balance may give a qualitative guide to the scaling of penetration with process speed. Consider full penetration taking place using beam power p in a plate of thickness d at speed v. A parallel sided kerf and melt region occur in the case of cutting and welding respectively. Let these have widths ω_c and $_w$ respectively. A significant fraction of the applied power p is deposited in the metal, the remainder being lost by reflection and through transmission. Of the power deposited, a fraction (perhaps of order $\frac{1}{2}$) corresponds to that required to heat and melt the volume of metal of interest, whilst the remainder is conducted into the work. It should be noted that the weld region can become a cut kerf with the application of an assist gas jet; use of a reactive gas has the effect of increasing the power deposited in the kerf. Therefore the approximation can be made that the volume of melt produced per unit time is proportional to the beam power applied. That is

$$P = k_c v d \omega_c$$

$$p = k_w v d \omega_w$$

where k_c, k_w are the constants of proportionality which contain contributions from reflectivity, specific enthalpy for melting, etc. Consider now two special cases:

In cutting, the width of the kerf may be comparable with the beam spot diameter and furthermore may remain substantially constant over a (limited) speed range. Thus from the above equation at constant power

$$vd = \text{constant, i.e. } v \propto 1/d$$

A plot of speed against thickness at threshold of cutting penetration will therefore have the form shown in Figure 30.4(a).

In welding, over part of the speed range, the aspect ratio of the melt, d/ω_w may tend to be maintained, i.e. $\omega_w \propto d$ and from the above equation, at constant power

$$vd^2 = \text{constant, i.e. } v \propto 1/d^2$$

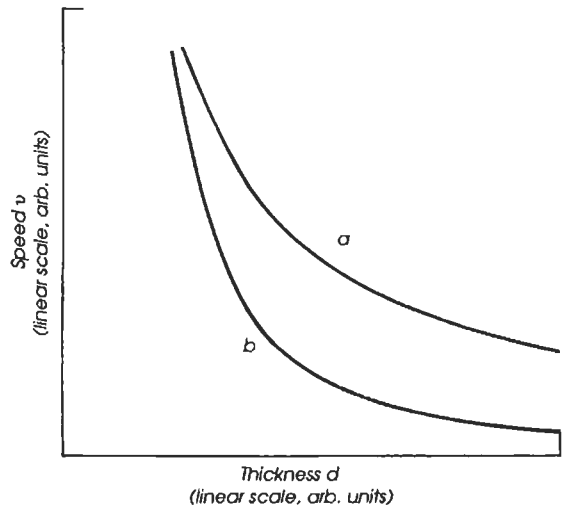


Figure 30.4 *Characteristic relationships between process speed and workpiece thickness based on simple energy balance and (a) kerf width independent of speed, (b) kerf aspect ratio (thickness/width) independent of speed*

A plot of speed against thickness at threshold of weld penetration may have the form also shown in Figure 30.4(b).

In practical application, processing may fall between these two special cases. Nevertheless, the energy balance approach permits some understanding of the characteristic shapes of plots of speed and thickness which are observed, and it provides a guide to extrapolating performance.

Surface transformation hardening

Here, a defocused beam is scanned over steel or cast iron, austenitizing a surface layer which then quenches by conduction into the bulk to give a martensitic layer. It is possible to make relatively simple and accurate predictions regarding process depths and speeds because the laser energy is deposited on the metal surface and is conducted, according to classical heat flow, into the meal.

Because the depth heated is small compared with the extent of the heating spot, it is quite appropriate to use a one-dimensional heat flow model which considers a heating flux F deposited for a time τ in the surface of a semi-infinite body. The dwell time τ corresponds to a beam spot, moving over a workpiece at speed v, and having length l in the travel direction where $\tau = l/v$. At the end of the heating pulse, the surface temperature T as a function of depth z is given by (Carslaw H.S. and Jaeger J.C., 'Conduction of Heat in Solids', 2nd edn, Clarendon Press, Oxford, 1959, p75).

$$T = \frac{2F}{K}\sqrt{k\tau}\ \text{ierfc}\ \frac{z}{2\sqrt{k\tau}} \left(\text{erfc}\ x = 1 - \text{erf}\ x \quad \text{and} \quad \text{ierfc}\ x = \frac{1}{\sqrt{\pi}} e^{-x^2} - x\,\text{erfc}\ x \right)$$

and the surface temperature T_s by

$$T_s = \frac{2F}{K\sqrt{\pi}}\sqrt{k\tau}$$

where K = thermal conductivity, k = thermal diffusivity $= K/\rho c$, ρ = workpiece density, c = workpiece specific heat.

In laser transformation hardening, it is usual to take the surface close to (but not above) the melting point. Thus in hardening steel, where $T_s = 1500°C$, $K = 0.35\ \text{W cm}^{-1}\,°\text{C}^{-1}$, and $k = 7.3 \times 10^{-2}\ \text{cm}^2\,\text{s}^{-1}$, the last equation gives

$$F\sqrt{\tau} \leqslant 1722\ \text{W cm}^{-2}\,\text{s}^{1/2}$$

if surface melting is to be avoided. Typically absorbed intensities of $3\,kW/cm^2$ and $6\,kW/cm^2$ might be used so that interaction times of $\leqslant 0.33\,s$ and $\leqslant 0.083\,s$ should be chosen respectively.

The resulting case depth can be estimated from the model by assuming that this is the same as the depth raised above austenitizing temperature. The temperature as a function of depth can be rewritten in terms of a surface temperature T_s

$$T = T_s \sqrt{\pi}\ \text{ierfc}\frac{z}{2\sqrt{k\tau}}$$

If hardening takes place down to a depth z' where $T = 850°C$, then since $T_s = 1500°C$

$$\text{ierfc}\frac{z'}{2\sqrt{k\tau}} \approx 0.3$$

i.e.

$$z' \approx 0.16\sqrt{\tau}$$

For the two cases considered above where $\tau = 0.33$ s and 0.083 s, $z' \approx 1$ mm and 0.5 mm respectively.

It is important to note from the foregoing that the process operates by the surface being heated very close to melting point. Thus a high degree of uniformity is required in the beam spot, otherwise melt strips may occur. Furthermore, a move towards greater case depth implies use of lower intensities in order to provide sufficient heat diffusion time. In practice, laser hardening is best suited to depths $\leqslant 1$ mm; beyond that self-quenching may become problematic and distortion may become noticeable. Also, in practice depth can be reduced by increasing processing speed—however there is a strong sensitivity in the interrelationship, and care is required.

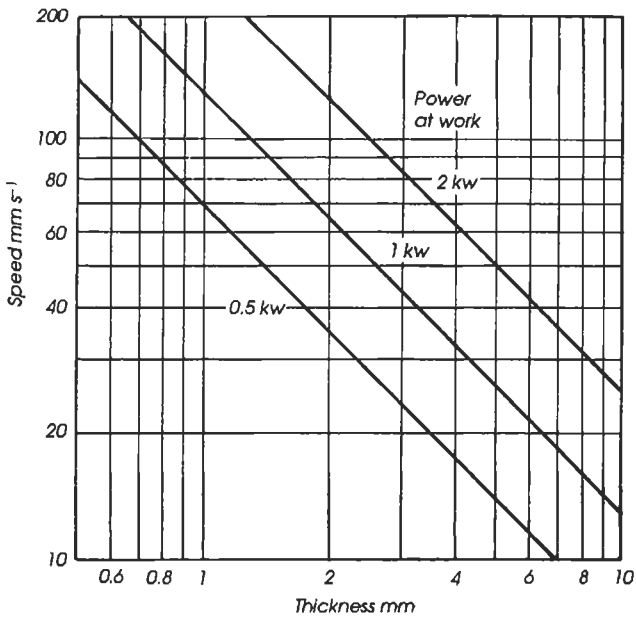
30.4 Cutting

The cutting process is based on location of beam focus at the surface of the (moving) workpiece, so that it melts the metal, and on provision of a jet of gas, usually coaxial with the laser beam, which displaces the molten material. This gas jet, if containing oxygen, may promote an exothermic reaction with the workpiece which enhances speed or penetration. For a well-optimized process, the resulting kerf can be narrow and parallel sided, the cut faces smooth (exhibiting striations of limited amplitude), the rear edges of the cut substantially free of adherent dross, and the heat affected zone (HAZ) narrow. Laser cutting currently occupies a niche which overlaps to some extent (depending on laser and workpiece) with electro-discharge machining, plasma cutting and abrasive water jet cutting. It is now believed that the following factors contribute crucially to the achievement of good cut quality. The radial intensity distribution of the beam should be narrow, steep sided and with little power in the wings; a Gaussian distribution appears suitable. The gas jet must be accurately centred on the beam interaction point and it should deliver high pressure into the kerf to promote efficient removal of material; however, care is required in the use of very high pressures since adverse supersonic shock structures may be present (and, particularly for lower laser powder, high gas flows may cause a deleterious chilling). Furthermore, an excess of oxygen can lead to too much burning of the material with a concomitant decrease in edge quality. For preference, the beam should be circularly polarized so that cutting performance is the same in all directions. The overall system (beam, jet, workpiece traverse) should be stable, smooth and free of jitter. However, the use of a pulsed laser beam may have advantages; it enables better control of energy input for the cutting of thin sections and fine details, and indeed it is claimed that careful matching of pulse frequency to cutting speed permits achievement of very smooth cut edges.

There is a growing body of data on cutting performance from laser manufacturers and researchers using a range of lasers and a wide variety of materials. Some care should be exercised in the use of such data because of the process dependences just described. For present purposes it is convenient to discuss performance by material type.

Steels

The vast majority of laser metal cutting is applied to steel, much of which is mild steel. Figure 30.5 provides a guide to cutting performance trends with oxygen assist; it shows illustrative data for both Nd:YAG and CO_2 lasers, bearing in mind that at present the former cover the range up to 1 kW and the latter up to 5 kW and above. Generally speaking, edge quality improves for the cleaner, more highly alloyed compositions; thus tool steel gives a better edge finish than mild steel.



Fiure 30.5 *Illustrative performance in oxygen-assisted laser cutting of mild steel; note that edge quality depends sensitively on processing conditions*

The cutting of stainless steel is more difficult because it resists formation of slag so that the dross is metallic rather than a friable oxide and it tends to adhere strongly to the rear edges. Indeed it is currently claimed that best edge quality on stainless steel is obtained with the use of N_2 assist gas at pressures up to 15 bar. In broad terms, the speeds of Figure 30.5 should be reduced by approximately 50% for stainless steel cutting.

Nickel alloys

Nickel alloys also exhibit a tendency to form a tenacious dross when laser cut. Again the cutting speeds of Figure 30.5 should be reduced by approximately 50%.

Titanium

Titanium is highly reactive, and therefore can be cut with considerable exothermic enhancement if oxygen is used. However, care is required. Not surprisingly, the cut edges are then highly oxidized. It is probably more relevant to utilize inert gas assist, e.g. argon, in which case oxide-free edges can result although the speeds of Figure 30.5 are again reduced by approximately 50%.

Aluminium

Aluminium is a good reflector, particularly at the CO_2 wavelength. For low average power CO_2 lasers, good focus spot quality is required, and pulsed operation is preferred. Speed is enhanced by use of oxygen. In all but the thinnest sections, the formation of a tenacious rearside dross occurs.

Laser metal cutting is well established industrially for a wide variety of applications. These range from two-dimensional profile cutting of sheet components to the three-dimensional trimming of pressings for the automobile industry. The process economics are best suited to prototype and medium batch production where the alternative of manufacturing blanking dies would be expensive.

A wide range of proprietary cutting equipment is now available. For very high precision, thin-section work this may consist of a Nd:YAG laser with lens focusing and a CNC X–Y table

to move the work. For thicker sections, where a CO_2 laser is more appropriate, a similar arrangement may be used or alternatively moving optics may be employed so that the focus head moves in X–Y over the fixed workpiece. Movements over several metres are now commonplace. For three dimensional cutting, the moving optics concept may be extended by the addition of a z axis together with one or two axes of rotation at the focus head. Five, or even six, axes are employed because it is desirable to cut with the beam normal to the workpiece surface. As an alternative to moving optics based on the foregoing cartesian system, robot arm systems are also available where the beam is conducted along the side of the arm, or even inside it. One of the claimed advantages of Nd:YAG lasers is that their use with fibre optics considerably simplifies beam delivery.

30.5 Drilling and engraving

The majority of drilling and engraving operations on metals are at present performed by pulsed Nd:YAG laser (although Nd:glass units may be used for drilling if lower repetition rates are acceptable). This is because the solid state lasers offer good coupling into metal surfaces, as well as pulse power densities which are higher than those obtainable from most industrial CO_2 units. The high focal intensities lead to vigorous material expulsion in drilling and, in engraving, legible symbols may be generated by surface evaporation and the creation of a very thin, slightly disrupted melt layer.

30.5.1 Drilling

The process arrangements for metal drilling are somewhat similar to those for cutting, i.e. the beam is focused on or close to the workpiece surface and a jet of assist gas is provided to aid expulsion of material. The laser is normally operated in free-running, pulsed-lamp mode (typical beam pulse length approximately 1 ms) and pulse energies up to 50 J may be employed. Empirical process optimization can be used to choose between the regimes of high repetition rate/low pulse energy and the converse. Two drilling techniques may be distinguished: percussion and trepanning. In the former the beam is kept fixed with respect to the workpiece, and the hole diameter is determined largely by spot diameter, values ranging from approximately 0.1 mm to 1.5 mm. Use of larger spots leads to an unacceptable reduction of focal intensity and larger holes are therefore drilled by the trepanning technique. The repetitively pulsing beam is then caused to describe on the work a circular trajectory, the diameter of which determines the diameter of the resultant hole. In principle, trepanned holes of arbitrarily large size can be drilled but in practice the method is best suited to diameters up to approximately 3 mm since thereafter mechanical drilling may offer a more cost-effective alternative. Currently, laser drilling in metal can give hole depths in excess of 20 mm. Under particular circumstances, depth to diameter aspect ratios may approach 50:1. The trepanning technique results in excellent axial symmetry. Holes are substantially parallel sided, although some degree of taper may be present, particularly in thicker workpieces. However, holes can be drilled having minimal heat-affected zones and recast layers as well as absence of microcracking. Furthermore, it is possible to drill holes which are inclined far off-normal to the workpiece surface.

Typical production applications include the drilling of metering and lubrication holes for the automotive industry and, most importantly, the large-scale drilling of cooling holes in nickel-alloy gas-turbine components for the aerospace industry.

30.5.2 Engraving

The engraving of uncoated metal requires localized application of the focused laser beam to the workpiece surface. A typical beam delivery system therefore incorporates a pair of galvanometer-type mirror units which permit steering of the beam over the work. Alphanumeric characters can then be created either via a dot-matrix array, or by tracing out the characters with a quasi-continuous beam. In the former, the laser is normally operated in free-running pulsed mode, synchronized with the line scanning system so that a dot may be produced at each co-ordinate of the array; the beam may then be switched on or off to write the required characters. In the latter, the laser is operated in Q-switched mode (tens of kilohertz) so that for typical mirror deflection speeds the written character is effectively continuous.

The advantages of laser engraving of metals include the contactless nature of the marking, the minimized metallurgical and mechanical damage and the ability to engrave through glass. A range of commercially-available equipment is available. Production applications include engraving of stock metal, engineering components and medical implants.

30.6 Welding

Laser welding now spans a significant thickness range, from submillimetre to greater than 10 mm. For thin section work, Nd:YAG lasers are generally preferred because of better beam coupling and the good control associated with pulsed operation (although rapid quenching between pulses may induce cracking in sensitive materials). For sections of one or two millimetres and upwards, CO_2 lasers are normally used but this range is becoming accessible to Nd:YAG with the advent of kilowatt power levels.

Although conduction-limited laser welding (carried out using beam intensities of around 5×10^5 W/cm^2) may be of interest in some applications, it is more usual to exploit the deep penetration capability of the beam by employing focused power densities of 10^6 W/cm^2 or greater. The workpiece surface then undergoes melting and vaporization which is sufficiently intense to disrupt the melt to form a capillary or keyhole, thereby enabling the beam to penetrate relatively deeply into the material. Using a pulsed or CW laser, and by suitably moving the work or beam, the keyhole translates along the join line, metal melting ahead and flowing round to solidify behind. The process, like that of electron beam welding but without the vacuum requirement, thus produces welds which are energy efficient, of low shrinkage (because they are narrow) and of low distortion (because they are parallel-sided). Laser welding is particularly suited to autogenous welding, close fit-up of the parts being normally required, although filler material can be added if a gap exists; filler may be used to improve weld properties. At higher CO_2 laser beam powers, plasma formation at the workpiece becomes important since it can be responsible for the broadening of the weld beads, a reduction in workpiece penetration and (more desirably) a smoothing of both weld surfaces. The plasma is frequently controlled by directing at it a jet of helium (which serves also to prevent oxidation). As in the case of cutting, the best penetration is obtained with good-quality, tightly focused beam spots. However, it should be noted that, particularly with pulsed lasers, it is possible to apply to the work power densities which are too high so that excessive evaporation and weld disruption occur. Figure 30.6 provides a guide to weld penetration trends in the welding of alloys of iron, nickel and titanium. Care should be exercised in the use of the figure because of the sensitivity of values to conditions such as spot quality, plasma control, etc; in any case, it is often

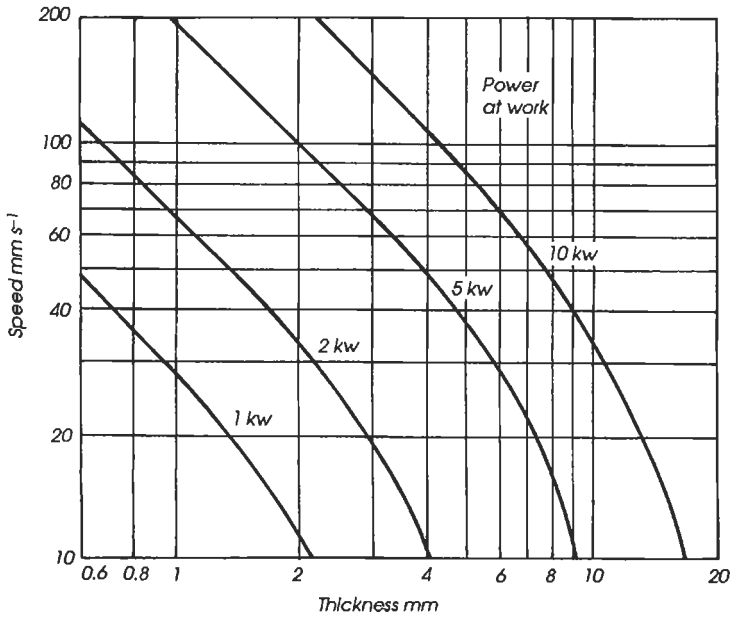


Figure 30.6 *Illustrative performance in laser welding of steel. Note: welding speeds slower than penetration-threshold values are required in order to create acceptable weld profiles; penetration at very slow welding speeds depends sensitively on pulsing and plasma effects*

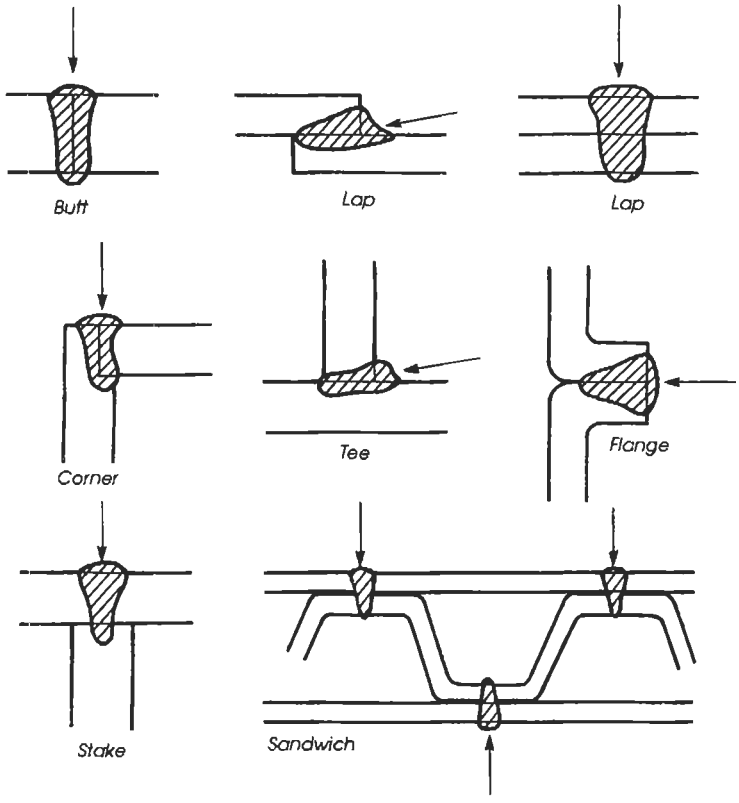


Figure 30.7 *Laser weld configurations*

necessary to reduce speed significantly below that at threshold of penetration, in order to achieve desirable weld geometry. However, the capability of the laser to carry out keyhole welding at ambient pressure can permit a novel approach to component fabrication. Indeed it is likely that the best exploitation of laser welding follows from a rethink of component design to match the process. Figure 30.7 shows a selection of possible joint configurations.

Laser welding is being applied to a wide range of materials. This has involved exploration of a new regime of welding, for although it may be argued that the process is similar to that of the electron beam, laser welding speeds are normally higher and cooling rates are faster so that different weld properties may result. Indeed there is no doubt much to be learned yet about process techniques such as the use of beam pulsing and spinning. Similarly, there is scope for more work to better understand the fine-scale scattered microporosity often seen in laser welding. At higher power levels more attention is required to the overlapping and ramping out of circumferential welds. Nevertheless, laser welding is now exploited in production to achieve high-integrity joints in a wide range of products. There follow comments on the weldability of a number of materials types.

Steels

Successful laser welding of mild steels requires choice of cleaner, low-carbon compositions which are not too rich in oxygen, sulphur or phosphorus otherwise weld disruption, porosity and solidification cracking may occur. If such effects are problematic, reduced welding speeds or use of appropriate fillers may help. Steels which have carbon equivalent greater than approximately 0.3% are difficult to weld without cracking because they have high hardenability and insufficient ductility to resist the shrinkage stresses encountered in many joint geometries. Thus the welding of planetary joints in gear assemblies may require shrink-fit assembly. Interest in the use of

multikilowatt power levels for deep penetration welding has led to studies in the joining of high-strength low alloy steels such as those used in pipelines and marine applications. The indications here are that low-carbon casts are greatly to be preferred for the achievement of restricted hardness and acceptable impact properties, although the use of appropriate filler may help. There is some evidence that flux-cored filler promotes in the weld an acicular ferrite microstructure have excellent impact properties.

Most austenitic stainless steels weld extremely well by laser. The welding of ferritic stainless, which is difficult by most processes because of grain growth and embrittlement, may benefit from the use of lasers because of reduced energy input.

Non-ferrous alloys

Titanium and nickel, and many of their alloys, exhibit good weldability by laser. On the other hand, the laser welding of aluminium and its alloys can require considerable care. This is partly because of high reflectivity (in the case of the CO_2 laser) but more importantly because in those alloys containing Mg and Zn selective evaporation of these elements can lead to porosity and weld disruption. The problem is greatly reduced when the alloying element is mainly copper.

30.7 Transformation hardening

By use of a diffuse beam, the surface hardening of carbon steels and irons can be achieved by martensitic transformation. The laser can be distinguished from alternative surface hardening techniques by one or more of the following attributes:

1. It characteristically operates as a rapidly moving source so that overall heat input (and therefore distortion) is minimized, and adequate quenching rates are obtained solely by conduction into the substrate.
2. The beam can be manipulated and directed into bores and conventionally inaccessible regions without the hindrance of supply cables and pipes.
3. Its heating patterns may be altered to suit the application.

The power densities (usually 10^3–10^4 W/cm^2) and speeds (or beam dwell times) are chosen to austenitize a relatively shallow case depth (usually $\leqslant 1$ mm) while avoiding surface melting. The workpiece surface may be given a prior coating of colloidal graphite to ensure efficient CO_2 laser energy absorption at the surface. As noted in Section 30.3.2., if access demands the use of an inclined CO_2 beam, it should be plane polarized to enable exploitation of the Brewster effect. Illustratively, for a 0.5 mm case depth, coverage per kilowatt is approximately 65 mm^2/s for cast iron and 135 mm^2/s for steel. Preferred materials for laser hardening are those in which the carbon is uniformly distributed, i.e. steels in quenched and tempered conditions, and cast irons having pearlitic matrices. In such materials, despite the brief thermal cycle, austenitization occurs quite quite uniformly with depth and a relatively flat hardness profile results. Nevertheless, adequate hardness may be obtained in steels having a coarse normalized structure, or in ferritic irons. This is because the near-surface layer experiences temperatures close to melting and sufficient carbon diffusion may occur to yield a useful martensite. Process conditions should be biased towards low intensities and long interaction times to aid diffusion. However, such cases generally exhibit a strong decrease of hardness with distance from the surface.

One of the key elements in laser hardening equipment is the means for achieving an extended, uniform heating pattern. A number of possible CO_2 laser beam techniques have been developed to varying degrees. These include: high-speed spot-rastering systems, beam scrambling based on faceted mirrors; and light pipes featuring multiple internal reflections. In some applications multi-mode operation of the laser resonator may yield a beam distribution which is adequately flat-topped to avoid causing melt strips. For treatment of components with special profiles, the use of tailored beam distributions may be required: for example the treatment of internal corners requires enhanced intensity there because of the increased heat-sinking; the converse is true of external corners and knife edges. The use of on-line surface temperature monitoring by optical pyrometry and with associated feedback control of the process parameters has been demonstrated as a useful adjunct to hardening equipment.

The production implementation of laser hardening is at present much less established than say laser cutting. Many of the reported applications relate to the automotive field and these include hardening of piston ring grooves and cylinder bores. In the latter application, the use of discrete spiral tracks seems preferred to overall hardening.

30.8 Surface cladding and alloying

These are surface treatment processes which involve substrate melting in conjunction with the addition of material to improve wear or corrosion resistance. In cladding, the additive is fused and then solidifies as a coating which is metallurgically bonded via the melting of only a very thin layer of the substrate; the composition of the final surface is close to that of the additive since it experiences little dilution by the substrate. On the other hand, in alloying there is significant mixing of molten substrate and additive and the resulting surface has composition and properties determined by contributions from the two. The attractions of using a laser for these processes concern localization of treatment, low cladding dilution, good geometrical control, efficient additive utilization and useful microstructures resulting from rapid cooling rates. Although there is research and development activity on fine-scale treatments relevant to the electronics sector (including use of Nd:YAG lasers) the current major effort is concerned with treatments for the automotive and power sectors performed mainly, but not exclusively, with CO_2 lasers. The additive may be in two forms: solid or gas. In the former it is preferable to use the material in powder form (cf. rod or wire for example) because not only are the deposit width and thickness more readily varied, but the powder promotes better coupling of the beam for CO_2 lasers. Normally the powder is supplied from a hopper via a delivery tube to the interaction point. Transport through the tube may be under gravity or via an inert gas stream. Alloying may also be carried out by arranging an appropriate gas atmosphere above the irradiated, molten surface; in this case it is usually adequate to direct at the interaction point a laminar flow of the gas and to avoid entrainment of air. The beam intensities used for cladding and alloying lie in the range 10^4–10^5 W/cm^2.

There is a natural tendency for cladding, rather than alloying, to occur when the additive has a lower melting point than the substrate. For example, a typically cobalt-based alloy (melting point 1340°C) can be clad on to steel (melting point 1500°C) under conditions of minimal substrate melting. Conversely alloying tends to occur when the additive has a higher melting point that the substrate; for example, in the alloying of silicon (melting point 1410°C) into aluminium (melting point 660°C) significant melting of the substrate and mixing with the silicon occur.

It should be noted that all surface melting processes, including those carried out by laser, tend to result in tensile stress in the as-treated layer. This is because the recast surface, as it solidifies and cools, tries to contract but is prevented from doing so by a relatively massive cold substrate. The effect is reduced by preheating the substrate and by heat-treatment after laser processing.

Production-line exploitation of laser cladding and alloying is still relatively limited. Most work appears to involve the cladding of cobalt-based hard-facing alloys on process plant components and on the interlock region of gas-turbine blading. Research and development effort is being directed towards alloying processes for titanium and aluminium. In the former, gas phase alloying using nitrogen results in a structure containing TiN and offering hardness up to 1000 HV and more. Alternatively, the introduction of carbides also leads to a surface offering high hardness. In the case of aluminium, alloying with silicon can be carried out very controllably to yield strengthened microstructures having hardnesses double that of the parent alloy.

30.9 Safety

In general, some of the basic requirements and guidelines for the safe handling of laser power supplies and laser beams are well established in existing safety standards such as BS4803:1983 in the UK. Whilst high power laser installations for metals working and materials processing are not addressed explicitly by such standards, nevertheless these installations usually come under Class 1 of the five classes identified in it. (More exceptionally, they may come under Class 4 operation in which, for example during beam alignment, an operator has to work without having the protection of a beam-tight protective enclosure around the equipment; in this case, reliance has to be placed largely on strict administrative controls.)

However, in Class 1 operation, the installation is regarded as a laser system contained within a protective enclosure from which personnel are excluded and which does not permit the escape of radiation above the 'Accessible Emission Limit' (AEL). For example, in the case of CW Nd:YAG or CO_2 lasers, it is prescribed that an operator must not encounter access to greater than 0.6 to 0.8 mW of beam power. Since the enclosed laser may have power of many kilowatts, it can be appreciated that much of the emphasis on safety provisions must centre on the engineering of the system so that there is a minimal risk that the beam can become errant and impinge on the enclosure and that, if it does, it is not permitted to penetrate the enclosure. The best current approaches tend to embrace a range of fail-safe design features which may include the following:

Optical components in the beamline must be selected, mounted and maintained with care to

that they do not fail and allow the beam to become errant. The workpiece must be presented in such a way that the beam couples to it and is not excessively reflected in a way to cause damage. The enclosure must be capable of containing an errant beam: at lower laser powers, it may be adequate simply to select materials such as brick or copper; at high powers, such constructions may need to be augmented by, for example, heat-sensitive scanners which can register beam impingement on the enclosure and then shut down the laser before penetration occurs. Preferably the processing should be continuously monitored: in some cases this may be done visually by a remote operators holding a dead-man's handle switch which they release if they see something amiss; alternatively for example a simple photo-sensitive detector can register light from the normal beam–workpiece interaction and enable continued operations (loss of light would imply that the beam had become errant so that the laser would then be shut down). Where one laser can be used with several workstations, a carefully designed system of beam switching, beam isolation and door interlocks must be employed to permit safe operator access for setting-up in one workstation whilst processing takes place in another.

It is important to note that, although the foregoing discussion has been concerned with safety issues to do with the laser beam, in a materials processing installation all due care must also be taken with associated hazards including: high voltage power supplies; moving manipulators and robots; toxic fume from welding and cutting; fire due to hot spatter as well as impingment of the transmitted or reflected beam; ultraviolet radiation from the welding plasma plume.

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31 Guide to corrosion control

31.1 Introduction

Metals may be chosen specifically for their resistance to a corrosive environment but in industry, where economic considerations affect the selection of materials, it may be less costly to choose a metal that has a comparatively short life, and carry out regular maintenance or replacement rather than a high initial capital investment in a resistant metal or alloy that will withstand the conditions of corrosion during the lifetime of the plant. There are many examples where either of these two extremes has been the more economic choice, and therefore a wide choice of materials is required. It may be that the most economical decision would be to use coatings (*see* Chapter 35), cathodic protection or control of the environment (inhibitors, etc.). Resistant materials will be listed, where these are available, followed by the less resistant metals and alloys where shorter lifetimes may be tolerated.

31.1.1 Types of corrosion

Corrosion damage to a metal or alloy can be (a) general or uniform corrosion, (b) Localized or pitting corrosion, and may be caused or enhanced by one or more of the following broad classifications:

bimetallic coupling (and dealloying),
crevice corrosion,
erosion corrosion,
stress corrosion cracking,
corrosion fatigue (and fretting corrosion),
hydrogen embrittlement.

31.1.2 Environments which cause corrosion

These may be broadly classified into three main groups:

1. *Natural*
 - Atmosphere — Humid, polluted condensation.
 - Water — Sea water, river, potable, condensation.
 - Soil — Buried structures.
 - Storage — Possible corrosion during storage, transit or erection.
2. *Chemicals*
 - Acids — Sulphuric, hydrochloric, nitric, phosphoric.
 - Alkalis — Sodium and calcium hydroxides.
 - Fertilizers — Nitrogen compounds, ammonia, organic acids.
 - Closed circulating systems — Concentration of river, well or sea water.
 - Manufacture of chemicals — 1000 + varieties.

Process chemistry	— Treatment; e.g. dyeing, pickling, food processing, paper-making.
High temperatures	— Oxidation of metals, exhaust fumes, flue gases.
Wet flue gases	— Combustion systems where gases can condense, i.e. dew point corrosion.

3. *Contact*

Wood	— Some vapours from wood are aggressive.
Polymers	— Some polymers, in contact with metals can cause corrosion.

31.1.3 Accelerating factors

Corrosion rates may be drastically changed when temperature, flow rates, pressures and concentrations of chemicals are varied; corrosion of metals from these parameters can therefore be regarded as an 'add on' factor and under certain conditions of temperature, pressure and flow the corrosion rates may then become excessive. There are many anomalies, e.g. mild steel is not attacked by very high concentrations of H_2SO_4 but rapidly at concentrations below 70% w/v. Copper can withstand sea water but is attacked when the flow rate is excessive.

31.1.4 Measurement of corrosion damage

Corrosion attack is not often uniform and it can be misleading to apply much of the published data which convert weight loss into penetration rate ($mm\,yr^{-1}$). For instance, mild steel in sea water corrodes at approximately $0.1\,mm\,yr^{-1}$, but pitting can occur up to $0.4\,mm\,yr^{-1}$ over a relatively small area of the total surface. In the case of intergranular attack at the metal grain boundaries a relatively small rate of attack can cause deep penetration so that whole grains drop out.

Corrosion rates must also be accompanied by the type of attack and in the case of pitting by the probability of finding the deepest pit at a certain depth.

In the case of high temperature oxidation and also for atmospheric corrosion, adherent corrosion products may be produced. The measurement of *weight gain* is then recorded.

Corrosion damage, although not excessive, can be very undesirable or even dangerous. When metals are under tensile or cyclic stresses a small amount of pitting could give rise to stress concentrations that lead ultimately to failure by cracking. Formation of corrosion products in a confined space can lead to 'oxide jacking' where the expansion suffered by the components can cause bursting and distortion. This has been widespread in some forms of concrete reinforcement where relatively mild corrosion can give rise to serious cracking of the nearby concrete.

31.1.5 Chemicals

For data on particular systems the following bibliography may be helpful.

SOURCES OF CORROSION RATE DATA

Three main sources of information:

1. data books;
2. national and international standards;
3. scientific journals and abstract literature.

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31.2 Bimetallic corrosion

Designers require structures and machines to have metals and alloys of differing mechanical properties in close proximity, e.g. mild steel backed copper bearing surfaces, lightweight aluminium structure on a mild steel base, and many fasteners, rivets, screws etc.

Table 31.1 CORROSION RATE IN mm yr^{-1} FOR BIMETALLIC COUPLING IN SEA WATER OF COMMON STRUCTURAL MATERIALS**

Cathodic member	M:Al*			M:*Mild steel**			M:*Zinc**		
M	10:1	1:1	1:10	10:1	1:1	1:10	10:1	1:1	1:10
Carbon	39	2–10	0.4	7.5	2–8	—	60	33	9
Carbon (Vs H30)	32	2–10	0.5						
Carbon (Vs NS4)	49	2–10							
Lead	0.5	0.15							
Silicon bronze	2.0	0.6		1.7	2.2				
10% Al bronze	2.4	0.6							
NiAl bronze (Vs H30)	2.8	0.7							
HY80	1.6	0.3	0.2	1.3	1.0				
Ni-Resist	0.7	0.06							
Ni Al bronze	2.4	0.15	0.09						
Tin	2.2	0.14							
CN30	1.7	0.1		2.5	0.6				
EN57	2.7	0.15		1.6	0.5				
Monel	2.2	0.12		3.3	1.4				
Mild steel (Vs H30)	3.0	0.16	0.04						
Mild steel	1.7	0.07	0.06				7.4	2.2	
LG4 gunmetal				2.8	1.8	0.04			
Lead				2.0	1.4				
Titanium				2.2	0.6		4.2	1.6	
EN58J				2.7	0.3				
Tin				2.8	0.35				
Aluminium							1.2	0.3	
Copper	4.5	0.66	0.05	6.7	0.3	0.12	14.5	0.5	0.27

* Includes effect of anode/cathode area ratio.
** Based on BS PD6484 (1979).

Table 31.2 CORROSION RATE (mm yr^{-1}) FOR CATHODIC MATERIALS CARBON, TITANIUM AND COPPER COUPLED TO VARIOUS ALLOYS

Anodic member	*Carbon*:M*			*Titanium*:M*			*Copper*:M*		
M	10:1	1:1	1:10	10:1	1:1	1:10	10:1	1:1	1:10
EN57	0.5	0.3		0.08	0.003		0.1	0.01	0.002
HY80	10	2–7					1.4	0.2	0.14
Ferralium 40V	0.007	0.01							
Ni-Resist	5.5	2					0.85	0.27	0.04
Tin	4	0.3		0.25	0.05		4.9	0.35	0.19
2% Al brass	0.4	0.1							
Si Al bronze	0.26	0.16		0.02	0.005				
Monel	0.02	0.02		0.004	0.002	0.002			
Silicon bronze	1.2	0.3	0.01						
Lead	0.5	0.16					1.5	0.46	0.06
Naval brass	0.5	0.22							

* Includes the effect of varying the anode/cathode area.

In these cases, providing the environment is sufficiently conducting, serious acceleration of corrosion may occur. However, compatibility can be achieved.

Table 31.1 gives the accelerating effect on coupling various materials with sea water as the conducting electrolyte. Comparable results may occur with other conducting chemical solutions. For electronic materials with thin metallic coatings in humid conditions, corrosion products may affect performance.

31.2.1 Bimetallic coupling associated with electronic materials

Various noble metals are used to provide good conducting, tarnish-free contacts which are reliable over the life-time of the equipment. These metals are used generally as very thin films (1–5 μm) are usually porous. They are therefore likely to act as a good cathode and induce corrosion even under slightly humid conditions. Thus, the connector can become covered with a thin film of corrosion products which can reduce the performance of the electronic device. Frequently this corrosion effect occurs in handling and in storage. It can also arise with unsatisfactory packaging, and the bimetallic coupling encourages attack.

Table 31.3 contains the combinations which have given satisfactory service and those that have been known to cause corrosion should the environment permit.

Table 31.3 SEVERITY OF GALVANIC CORROSION FROM METALLIC COMBINATIONS
Coatings are shown in brackets: (Ni)Cu = nickel-plated copper; (r.Sn)Cu = reflowed tinned copper; (s.d.)Cu = solder-dipped copper.

Completely satisfactory	*Satisfactory slight corrosion*	*Borderline moderate corrosion*	*Unsatisfactory severe corrosion*
Cu–(Ni)Cu	Cu–(Ag)Cu	(Au)Cu–(s.d.)Cu	Al–Brass
Cu–(Au)Cu	(s.d.)Cu–(Sn)Al	(Sn)Al–(Ni)Cu	Al–Cu
(Sn)Cu–Al	Cu–(Sn)Cu	Al–(s.d.)Al	(Sn)Al–Cu
(Sn)Cu–(Ni)Cu	Cu–(s.d.)Cu		Al–(Ni)Cu
(Sn)Cu–(s.d.)Cu	Cu–(r.Sn)Cu		Al–(Ni)Brass
(Sn)Brass–Al	(Ag)Cu–(Sn)Cu		Al–(Ag)Cu
(s.d.)Cu–(Ni)Cu	(Ag)Cu–(s.d.)Cu		(Sn)Al–(Ag)Cu
(Ni)Cu–(Au)Cu	(Au)Cu–(Sn)Cu		Al–(Au)Cu
(Ni)Cu–(Ag)Cu	Al–(Sn)Al**		(Sn)Al–(Au)Cu
(Au)Cu–(Ag)Cu			
Al–(Sn)Al*			

* No copper undercoat. ** Zincate process.

31.2.2 Dealloying-selective dissolution as a form of bimetallic corrosion

A special case of bimetallic corrosion occurs for certain alloys where the base metal can be preferentially dissolved. Copper–zinc alloys are prone to this corrosion, and dezincification can be a serious corrosion problem resulting from the chemical composition of some natural waters. In particular, high chlorides and high temperatures lead to corrosion of the zinc alloying element leaving the copper as a porous mass. The component may keep its shape but has weak mechanical properties. Information about these water supplies may be obtained from the British Non-Ferrous Metal Association. The standard test, ISO 6509, for susceptibility to dezincification requires the immersion of a sample of the alloy in 1% copper chloride at 75°C for 24 h. The corrosion can be reduced by a 1% alloy addition of Sn or by 0.02–0.06% of Sb or P. Copper alloys with resistance to dezincification are given in Table 31.4.

Table 31.4 SINGLE AND TWO PHASE COPPER–ZINC ALLOYS AND THEIR SUSCEPTIBILITY TO DEZINCIFICATION

Alloy type	*Dezincification*	*Alloy addition to reduce rate*
Copper 85% and above	No	—
Copper 70–85%	Susceptible	Arsenic up to 0.1%
Copper 60–70%	Susceptible	Tin up to 1.0% with arsenic 0.1%

31.3 Crevice corrosion

Many engineering designs place metals together for joining, or create narrow slots or pockets where liquids could be retained. Such crevices include screw threads, nuts, washers, gaskets, some weldments, heat exchanger rolled in tubes, valve packings, etc. In neutral aerated waters there is the strong possibility of corrosion within these crevices, particularly with strongly passive metals in chloride solutions such as sea water. Practically all metals can suffer from this form of attack and the usual remedy is to remove the crevice by careful design of the fit of the components, or by sealing or coating. Table 31.5 gives an order of resistance to crevice corrosion which shows that some metals show good resistance. It is interesting to note that many of the popular stainless steels can be affected to a serious extent by crevice corrosion.

Table 31.5 RESISTANCE TO CREVICE CORROSION

Metal	*Very resistant* →	*Moderate corrosion*		→	*Severe corrosion*
Mild steel Low alloy steel		Sea water			
Cupro nickel Cu 10Ni 1.5Fe	Sea water	Neutral solutions			
Cu and Cu/Zn	√				
Titanium and Ti alloys	√ (ambient temp)	95 °C			Halide* and sulphate solns
Stainless steel 10% H_2SO_4 RT	321	316	304	302	13% Cr
10% H_2SO_4 + NaCl	316	321	302	304	16% Cr
Fe 18Cr 13Ni 3Mo 2Si NNG	√				
Fe 18Cr 14Ni 2Mo NiTi	√				
Fe 18Cr 24Ni 3Mo 2Cu	√				
Fe 20Cr 25Ni 5Mo 1.5Cu	√				
Fe 18Cr 10Ni 2.5Mo 2.5Si	√				
Fe 25Cr 2Mo(duplex)	√				
Fe 25Cr 6.5Ni 3Mo(duplex) 0.3 W	√				
Nickel alloys					
Hastalloy 'C'	< 60 °C				
Inconel 625	< 60 °C				
Cobalt alloys					
Vitallium	< 60 °C				

* Ti 0.2% Pt 2% Mo(or 2% Ni) relatively more resistant.

31.4 Corrosion/erosion resistant materials

Flowing electrolytes can increase corrosion rates that are dependent on diffusion. This usually applies to aerated solutions. Corrosion rates in mm yr^{-1} for flowing sea water are given in Table 31.6 and for copper central-heating tube in Table 31.7.

Table 31.6 CORROSION/EROSION IN FLOWING SEA WATER AT AMBIENT TEMPERATURE
Corrosion rate mm yr^{-1}

	Flow rate m s^{-1}		
Metal	*0.3*	*1.2*	*8.0*
Carbon steel	0.16	0.33	1.0
Ni resist.	—	—	0.8
Cast iron	0.2	—	1.25 (7 at 28 °C)
Silicon bronze	0.005	0.08	1.6
Admiralty brass	0.08	0.08	0.7
Aluminium bronze	0.16	—	1.0
Aluminium brass	0.08	—	0.5
Cu, 10% Ni, 1% Fe	0.2	—	0.4
Cu, 30% Ni, 0.05% Fe	0.08	—	0.8
Cu, 30% Ni, 0.5% Fe	0.005	—	0.16
Monel 400	0.005	—	0.005
Stainless steel Type 316	0.004	—	0.005
Hastalloy C	0.005	—	0.05
Titanium	0	—	0
Inconel 625	0	—	0

Table 31.7 EROSION OF COPPER TUBING IN CENTRAL-HEATING SYSTEMS
12 months' tests—corrosion rate in mm yr^{-1}

Temp.			*Flow rate* m s^{-1}			
°C	*pH*	*Aeration*	1	3	6	12
30	8	Yes	—	—	—	0.03
65	8	Yes	—	—	0.015	0.07
65	8	Yes	—	—	—	0.07
90	8	Yes	0	0.05	0.07	0.07
65	8	No	—	0.05	—	—

31.5 Cavitation

Table 31.8 CAVITATION—HIGH VELOCITY LIQUID FLOW

Highly resistant	*Good resistance*	*Poor resistance*
Stellite 12	Monel 500 5% Si	Aluminium alloys
Stellite 4	Aluminium bronze	Mild steel
Stellite 6	White cast iron	Alloy cast iron
	Silicon iron	Copper
Titanium 99%	High strength Martensitic steel	Silicon bronze
Ti 2.25Al 4Mo 0.2Si 11Sn		Manganese brasses
	Stainless-Martensitic steel EN 5C	Aluminium brass
		Admiralty brass
	Austenitic stainless steel EN 58J	Cu 10Zn

31.6 Corrosion fatigue

This form of failure by cracking is responsible for about 20% of the failures in the chemical process industry.

Corrosion fatigue is the failure of a material caused by cyclic alternating stress in the presence of a corrosive environment. All metals are known to fail at stresses below the yield stress when under cyclic loading. The effect of corrosion is in general to reduce even further the stress level at which failure occurs.

31.6.1 Measurement

It is usual to measure the number of cycles (N) to failure at various applied stress levels (S), the so-called S/N curves. For some metals there is a 'limiting stress level' below which the metal will not fail by cracking. For many metals there is no 'limiting stress level' and for these materials the stress level which leads to failure in a certain number of cycles is recorded, e.g. 10^7 or 10^8 cycles.

31.6.2 Effect of sea water on corrosion fatigue resistance

Table 31.9 gives results for various materials and shows the lowering in strength as a result of cyclic loading. This table is based on laboratory testing and is only a guide. It does, however, demonstrate that account should be taken of the effect of vibration and cyclic loading.

Table 31.9 CORROSION FATIGUE OF ALLOYS IN SEA WATER
Conditions: ambient temperature in flowing sea water (0.6 m s^{-1}) mean stress zero: 10^8 cycles.

Alloy	*UTS* M Pa	*Corrosion fatigue limit* 10^8 *cycles* M Pa	% *reduction in strength to*
Mild steel	400 to 500	14	96.5
Titanium 6% Al–4% V	1060	610	42
Copper alloys			
Monel	1210	179	85
Al bronze	710	152	79
70% Cu–30% Ni	572	62	89
Stainless steels			
304	545	104	81
304L	545	97	82
316	586	97	83
316L	545	90	84
13% Cr–1% Ni (cast)	717	69	90
Nickel alloys			
15% Cr, Mo 3%, Fe 7% (IN–12)	1415	480	66
Inconel 718 19% Cr–3% Mo–18.5% Fe Nb + Ta 0.08 mm	1304	414	68
0.4 mm	1030	345	67
Hastalloy C	745	220	70

Table 31.10 EFFECT OF ENVIRONMENT ON CORROSION FATIGUE LIMIT AT 10^7 CYCLES MPa 20°C MEAN ZERO STRESS

Material	*Air*	*Sea water*	*Other corroding solution*
0.17% C steel	218	63	
0.50% C steel	281	70	
15% Cr steel	328	203	
17% Cr–1% Ni steel	422	265	
18% Cr–8% Ni steel	390	280	10% H_2SO_4
Type 304			210
Magnesium alloy (2.5% Al)	91	16	
Duralumin (Al–4% Cu)	125	55	
Mild steel	290	3% NaCl	De-aerated distilled water
		200	290
		De-aerated 3% NaCl	De-aerated distilled water
		290	250
Aluminium zinc magnesium alloy	140	3% NaCl 50	
Shot peened surface	200	3% NaCl 100	

31.7 Stress corrosion cracking

Table 31.11 STRESS CORROSION CRACKING (SCC) IN MILD AND HIGH STRENGTH STEELS

Material	*Conditions affecting stress corrosion cracking*
Mild and low carbon steels	Accelerated SCC by: NaOH, KOH, Na_3PO_4, HNO_3, $NaNO_3$, $Ca(NO_3)_2$ NH_4NO_3, $(NH_4)_2CO_3$, bicarbonates, fuming H_2SO_4, $FeCl_3$. $Fe(Al)_3O_3 + Al_2O_3 + CaO$, ethanolamine + H_2S + CO_2, H_2O + CO + CO_2 HCN
	Hot nitrate solutions: C 0.005–0.19% susceptible 0.09–0.19% C { Moderate plastic deformation increases susceptibility Large amount of cold work decreases susceptibility Welds with up to 0.26% C in hot nitrates susceptible Welds stress annealed at 600 °C prevents stress corrosion cracking Time to failure decreased as concentration of nitrate increases in boiling solutions. Temperature increase decreases time to failure. Alloying with Cr, Ta, Nb, Ti, Mn reduces susceptibility Inhibitors reduce susceptibility. Cathodic protection in some cases
Mild and low carbon steels—*cont.*	*Caustic solutions:* C 0 → 0.02% increases susceptibility C > 0.02% increases time to failure Fully killed steels very susceptible Semi-killed steels slightly susceptible Low C rimming steels very resistant to SCC Temperature increase reduces time to failure. The higher the temperature the lower the concentration at which cracking occurs. Plastic deformation increases SCC. Annealing prevents SCC unless deformation is beyond yield stress
High strength steels (yield > 1000 MPa)	Below 1000 MPa yield stress hardenable steels are generally immune from SCC Above 1000 MPa yield:—
	Chloride solutions: Increase above 0.25% NaCl has little effect on time to fracture by SCC. Temperature has little effect in range 15–80 °C. pH has little effect but above pH 10 susceptibility is reduced. Hydrogen embrittlement and cathodic protection can increase susceptibility to SCC

Table 31.12 CONDITIONS FOR STRESS CORROSION CRACKING IN STAINLESS STEELS

Environment for SCC:	*Chloride solutions*	H_2S *with or without chlorides*	*Caustic solutions*	*Polythionic acid*
Susceptible alloys:	*Types* 304, 316 *martensitics*	*Martensitics ferritics ferritic-austenitics*	*Types* 304, 316	*Types* 304, 316
Temperature °C	> 70	< 60	> 120	Ambient
Chloride content	10 p.p.m. temp. dependent	—	—	—
PH	> 2.0 At lower pH general corrosion for susceptible alloys	pH affects threshold stress	> 12	—
Stress level	Moderate	High	Moderate	Low
Metallurgical condition	All	All	All	Sensitized

Table 31.13 STAINLESS STEEL GRADE SELECTION IN ENVIRONMENTS WITH RISK OF STRESS CORROSION

Solution	*Conditions* *Temp.* °C	*Chloride content*	*Recommended grade*
Chloride solutions	≤ 70	Low	304 or 316 depending on risk of pitting
	≤ 70	High	2RE 65,[1] high pitting resistance
	≥ 70	Low	2RE 60[2]
	> 70	High	2RE 65[1]
	> 300	Low	SANICRO 30[3]
H_2S-containing solutions	> 60	None	316
	> 60	Low	2RE 60[2]
	> 60	High	2RE 65[1]
	< 60	None	316
	< 60	Present	2RE 65[1]
Caustic solutions	< 120	Caustic conc. < 20 wt. %	304, 316
		> 20 wt. %	SANICRO 30[3]
Polythionic acid	—	None	321 or 346 stabilized
	—	Present	SANICRO 30[3]

1) 2RE65 Fe 25 Ni, 19.5 Cr, 4.5 Mo, 1.5 Cu
2) 3RE60 Fe 18.5 Cr, 4.5 Ni, 1.6 Si, 2.5 Mo, 0.02 C
3) SANICRO30 Fe–Cr–Ni; small additions of Mn, Cu, Al, Ti.

31.8 Hydrogen embrittlement

Stress corrosion cracking susceptibility can be connected with hydrogen embrittlement. Hydrogen embrittlement may be caused by pick up of hydrogen from melting, welding, electroplating, corrosion reactions or hydrogen gas storage. Table 31.14 gives the order of susceptibility to hydrogen embrittlement of a range of common metals.

Table 31.14 SUSCEPTIBILITY TO HYDROGEN EMBRITTLEMENT

Susceptibility ranking in decreasing susceptibility	*Material*
High susceptibility	High strength steels at high yield strength High strength nickel steels Medium strength and low strength steels Iron–silicon single crystals Cobalt alloys
Low susceptibility	Stainless steels: 310, 304
Little or no susceptibility	Copper alloys Stabilized stainless steels Aluminium alloys Molybdenum

Note: Carbon and alloy steels in H_2S atmospheres should be annealed and tempered to a strength less than 800 MPa.

31.9 Fracture toughness under corrosive conditions

Linear elastic fracture mechanics applied to stress corrosion cracking contributes to the quantitative assessment of the effect of crack size and crack growth rate. The crack rate velocity depends uniquely on the plain strain stress intensity, *KI*, and there is a common relationship between these parameters. Tolerable flaw sizes and acceptable slow crack growth rate for many structures can be calculated from this parameter.

31.9.1 Stress corrosion intensity factor *KISCC*

KISCC may be defined as the minimum stress below which subcritical size cracks do not grow. For certain environments and flaw sizes, the stress intensity may be exceeded, if in the specific environment the crack growth rate is not excessive.

$$\text{Critical crack size } C = X\left(\frac{KISCC}{\sigma_y}\right)^2$$

where X is a factor dependent on the crack geometry,
σ_y is the yield stress,
C is maximum allowable crack length if crack growth is to be avoided.

Note: If *KISCC* is in MPa $m^{1/2}$ and σ_y in MPa, then C is in metres. For stress intensity greater than *KISCC* a crack will grow to the critical crack size usually at a constant crack velocity, the magnitude of which depends on the chemical environment. If the crack velocity is sufficiently low, the structure may be safe within its design life. Temperature also affects the magnitude of the crack velocity.

See also Chapter 21, 'Mechanical Testing'.

Table 31.15 KIC AND KISCC VALUES
Assume critical crack size $C = 200\ (K/\sigma)^2$, where σ = yield stress, in MPa; C = crack length, in mm.

Alloy	*in air* *KIC* MPa $m^{1/2}$	*C* mm	*Environment which induces stress corrosion*	*KISCC* MPa $m^{1/2}$	*C* mm
Copper alloys					
Cu–30% Zn	200	13	NH_4OH pH7	1	0.003

Ultra high strength steels virtually independent of composition variation, P and S have little effect on *KIC* and *KISCC*.

Table 31.15 *KIC AND KISCC VALUES—continued*

Alloy	*in air* *KIC* MPa $m^{1/2}$	*C* mm	*Environment which induces stress corrosion*	*KISCC* MPa $m^{1/2}$	*C* mm
Iron–steel alloys					
Mild steel 0.2 C 0.8 Mn	120	15	10 M NaOH (boiling)	1	0.001
High strength steels					
Steel	36	—	Distilled water	20	—
reinforcing	31	—	$Ca(OH)_2$ (sat.) + NaCl	22	—
bar	31	—	pH 120		
	42	—	above but coupled to Mg	18	—
			above but stress relieve at 430 °C	25	—
Martensite steel			yield stress 1400 MPa		
0.47 C 1.14 Cr			Natural sea water	12–20	0.015–0.04
0.82 Mn 0.6 Ni	~100	~1.0	3.3% NaCl		
1.0 Mo Fe rem (D6–AC)			Distilled water		
			Hydrazine inhibitor 2%	25	—
High carbon steel					
0.84 C 0.26 Si	77	0.5	Tensile strength		
0.86 Mn			1500 MPa	48	0.2
			Distilled water 600 ppm Cl^- + 1300 ppm SO_4^{2-}	48	0.2
			Cathodic protection	42	0.16
High strength alloy steel			3.5% NaCl, 20 °C Heat treatment to		
4340 steel	66	0.5	1420 MPa	20	0.05
0.3 C, 0.63 Mn			1000 MPa	94	1.0
0.87 Cr, 0.39 Mo,			H_2S gas } 0.5 MPa	33	—
2.29 Ni			pressure } 0.35 MPa	30	—
Stainless steels					
13% Cr steel					
(0.2% C)	60	—	Distilled water 23 °C	17	—
			3.5% NaCl	12	0.008
18% Cr, 8% Ni,	200	75	42% $MgCl_2$–boiling	10	0.18
Stainless steels—cont.					
16% Cr, 4% Ni, 4% Cu, 1% Mn, 1% Si,			3.5% NaCl		
Nb–Ti–0.3%, 0.07% C.	187	—	tempered at 1150 °C	140	—
	124	—	tempered at 900 °C	87	—
(17-PH alloy)			Cathodic protection		
			by coupling with Zn	33	—
			(900 °C with Al	60	—
			temper) with Mg	29	—
High alloy steels					
18% Mn, 5% Ni	145	—	Hot aqueous halide solutions	8	0.01
13% Co, 10% Ni,	140	1.4	3.5% NaCl at 20 °C		
1% Mo, 0.15% C.			at 0.2% proof { 1660 MPa	19	0.03
Prec. hardened			stress { 1440 MPa	33	0.10

Table 31.15 KIC AND KISCC VALUES—*continued*

Alloy	*in air* *KIC* $MPa\,m^{1/2}$	*C* mm	*Environment which induces stress corrosion*	*KISCC* $MPa\,m^{1/2}$	*C* mm
High-alloy steels—*continued*					
9% Ni, 4% Co, 0.45% C	67	0.4	Martensitic yield at 1650 MPa	15	0.02
	100	1.0	Bainitic, yield at 1500 MPa	18	0.04
Aluminium alloys			3.5% NaCl + 0.2 M $Na_2Cr_2O_7$ + 0.07 M Na acetate, + acetic acid to pH 4.0		
Type 2024	18	—	Resistant temper T851	14	—
	25	—	Susceptible, temper T351	12	—
Type 2219	22	—	Resistant, temper T87	22	—
	22	—	Susceptible, temper T37	12	—
Type 7075	24	—	Resistant, temper T 7351	20	—
	20	—	Susceptible, temper T651	4	—
Ag–3Mg–7 Zn	25	—	Aqueous halides at 20 °C	5	0.04
Titanium alloys Ti–6Al–2Nb			NaCl solutions		
1% Ta + 0.8% Mo	150	9	Heat treated to 700 MPa	116	5
	138	6	Heat treated to 800 MPa	44	0.6
Ti–6Al–1V	60	1.1	0.6 M KCl	20	0.12
Ti–3Al–8V	35	0.2	Methyl alcohol–HCl	6	0.006

REFERENCES TO TABLE 31.15.

H. L. Craig (Ed.), 'Stress corrosion—new approaches', ASTM–STP 610, Philadelphia (1975).

R. W. Staehle *et al.*, 'Stress corrosion cracking and hydrogen embrittlement of iron-based alloys', NACE, 5 (1973).

31.10 Atmospheric corrosion

Table 31.16 UNIFORM CORROSION* IN INDUSTRIAL ATMOSPHERE

Alloy	*Uniform rate of corrosion* $mm\,yr^{-1}$
Mild steel	0.125
Wrought iron	0.200 (% Si < 0.1%)
Wrought iron	0.100 (% Si > 0.3%)
Copper-bearing mild steel	0.100
Fe, 1% Cr, 0.5% Cu	0.075
Aluminium	0.005
Zinc	0.006
Copper	0.007
70/30 brass	0.020
Nickel	0.010
80 Ni 20 Cr	0.004
18 Cr 8 Ni stainless steel	0.001

* Pitting may take place and penetration can be 2–5 times uniform values.

Table 31.17 UNIFORM CORROSION* IN SPECIAL ATMOSPHERES

Environment	*Rate of uniform corrosion for mild steel* $mm\,yr^{-1}$
Domestic kitchens and bathrooms	0.0025–0.001
Laundry	0.0075
Sulphuric acid plant	0.048
Paper mill	0.068
Pickling sheet steel	> 0.45

* Pitting may occur and penetration may be 2–5 times uniform rate.

31.11 High temperature oxidation resistance

Oxidation of metals in air produces a relatively thick oxide scale dependent on temperature. Above certain high temperatures the scale becomes excessive and will spall away to give wastage. For close fitting components, such as bolts, values etc. this could cause seizure and cracking.

Table 31.18 HIGH TEMPERATURE OXIDATION OF STEELS

Steel	*Temperature* °C *for oxidation* >0.127 mm yr^{-1}
Plain carbon	580
Fe 0.5% Mo	600
Fe 0.5% Cr, 0.5% Mo	600
Fe 2.25% Cr, 1% Mo	613
Fe 5.0% Cr, 0.5% Mo	607
Fe 9% Cr, 1% Mo	670

Table 31.19 RECOMMENDED TEMPERATURE LIMIT FOR OXIDATION OF VARIOUS ALLOYS IN AIR

Metal	*Temperature limit* °C
Carbon steel	450
2½%Si, 1%Al, 1%Mo steel*	700–900
½%Mo steel	500
½%Mo, 1%Cr steel	550
½%Mo, 5%Cr steel	550
1% Mo, 9%Cr steel	550
12%Cr, Mo, V steel	575
18%Cr, 8% Ni stainless steel	650
12%Cr, 8%Ni, 1% Nb steel	650
19% Cr, 11%Ni, 2%Si steel	1 000
23%Cr, 14%Ni steel	1 000
23%Cr, 30%Ni steel	1 100
80%Ni, 20%Cr	900
60%Ni, 20%Cr, 20%Co, Al, Ti	900
55%Ni, 15%Cr, 20%Co, 5%Mo, 5%Al and Ti	1 100

* E. A. Brandes, Fulmer Research Institute, Special Report No. 2, 1956.

31.12 Contact corrosion

Contact corrosion can be a serious problem in packaging and in electronics. As miniaturization and sophistication of electronic devices have increased, the hazard presented by corrosion is often the limiting factor inhibiting the attainment of expected levels of reliability.

Semiconducting devices, switches and miniaturized VHF circuits are all particularly sensitive to the slightest reaction on critical surfaces, and in devices calling for the highest levels of reliability even the most inert of the phenolic, epoxide and silicone resins are not considered to be fully acceptable; corrosion of electronic assemblies may often be enhanced by migration of ions to sensitive areas under applied potentials, and by local heating effects associated with current flows.

For more information see: P. D. Donavan in L. L. Shreir, 'Corrosion', Vol. 2, Butterworths, London, 1976 and W. H. Abbott, 'Corrosion of Electrical Contacts', *Brit. Corr. J.*, 1989, **24**, No. 2.

Table 31.20 CONTACT CORROSION DANGERS: POLYMERS ETC.

Material	*Severity of corrosion**	*Volatiles evolved and remarks*
Rubbers, elastomers and adhesives		
1. Natural rubber		
(*a*) Non-vulcanized	Slightly corrosive on prolonged exposure	Formic and acetic acid evolved
(*b*) Vulcanized	Slightly–moderately corrosive	Hydrogen sulphide and sulphur dioxide evolved
2. (*a*) Synthetic rubbers	Non-corrosive at ambient condition—most are corrosive above 100°C	Many are chlorinated and evolve HCl on heating; Hypalon may also emit sulphur dioxide
(*b*) Polysulphide rubbers (cold curing)	Moderately corrosive–very corrosive	Formic acid; the catalysts used are peroxides
3. Silicone polymers	Non-corrosive–very corrosive	Acetic and formic acids. Some single-pack silicone sealants cure by hydrolysis of acetoxy groups releasing acetic acid and are very corrosive; some two-pack formulations evolve formic acid and are corrosive, and others are reputed to be among the most inert polymers
4. Phenol and ureaformaldehyde glues	Slightly corrosive–very corrosive	Formaldehyde, phenol, ammonia and HCl may be evolved. Various acids and salts that yield acids (e.g. formic acid and hydrochloric acid) are used in cold-set formulations. Volatiles evolved during cure may be absorbed by the materials being bonded
Thermoplastics		
1. Polyvinyl chloride (PVC) (and other chlorinated thermoplastics)	Non-corrosive at ambient temperature (but *see* column 3); moderately–very corrosive at 70°C	Hydrogen chloride (HCl). May become corrosive at ambient temperature if irradiated with UV radiation or in the presence of certain contaminants, e.g. zinc ions
2. Fluorinated thermoplastics (e.g. PTFE)	Non-corrosive at ambient and moderate temperatures; very corrosive above about 350°C	Decompose to release HF and F_2
3. Nitrocellulose	Slightly–very corrosive	Oxides of nitrogen may be evolved progressively with ageing
4. Nylons		
(*a*) Nylon 6	Corrosive	Acetic acid; formulations frequently contain acetic acid additions as molecular weight regulators
(*b*) Nylon 66	Non-corrosive	
5. PVA (polyvinyl acetates and alcohols)	Non-corrosive–very corrosive	Acetic acid released; corrosivity dependent on conditions and formulation (degree of hydrolysis and presence of stabilizers and inhibitors)
6. Cellulose acetate	Slightly corrosive	Acetic acid may be released

Table 31.20 CONTACT CORROSION DANGERS: POLYMERS ETC.—*continued*

Material	*Severity of corrosion**	*Volatiles evolved and remarks*
7. Polyacetals		
(*a*) Homopolymer	Slightly corrosive at ambient temperature, more corrosive above 40°C	Acetic acid and formic acid evolved (acetic acid may be used as an end-stopper)
(*b*) Copolymer (formaldehyde and 10% ethylene oxide)	Usually non-corrosive at ambient temperatures, corrosive above 45°C	Formic acid evolved (if arduous moulding conditions have been used, the polymer may be corrosive at ambient temperatures)
8. Polyolefines, polyesters, polycarbonates, polystyrene, polysulphone, polyphenylene oxide and polymethylmethacrylate	Non-corrosive at ambient temperatures	
Thermosetting resins		
1. Cross-linked polyesters		
(*a*) Cold cured polyesters	MEKP catalyst and cobalt naphthenate accelerator—very corrosive. Other peroxide catalyst systems slightly–moderately corrosive. Irradiation or non-oxidizing catalyst } non-corrosive	Formic and acetic acids evolved. Corrosivity is determined largely by the catalyst used, but is also affected by the formulation, in particular diethylene glycol gives more corrosive resins than does propylene glycol
(*b*) Hot cured polyesters	Non-corrosive–moderately corrosive	

* Refers directly to Zn, Mg and steel.

Defence Guides, DG-3A, 'Prevention of corrosion of zinc and cadmium coatings by vapours from organic materials', HMSO.

Table 31.21 CORROSION BY CONTACT WITH WOOD

Wood	*Classification*	*Typical* pH *values*
Oak	Most corrosive	3.35, 3.45, 3.85, 3.9
Sweet chestnut	Most corrosive	3.4, 3.45, 3.65
Steamed European beech	Moderately corrosive	3.85, 4.2
Birch	Moderately corrosive	4.85, 5.05, 5.35
Douglas fir	Moderately corrosive	3.45, 3.55, 4.15, 4.2
Gahoon	Moderately corrosive	4.2, 4.45, 5.05, 5.2
Teak	Moderately corrosive	4.65, 5.45
Western red cedar	Moderately corrosive	3.45
Parana pine	Least corrosive	5.2 to 8.8
Spruce	Least corrosive	4.0, 4.45
Elm	Least corrosive	6.45, 7.15
African mahogany	Least corrosive	5.1, 5.4, 5.55, 6.65
Walnut	Least corrosive	4.4, 4.55, 4.85, 5.2
Iroko	Least corrosive	5.4, 6.2, 7.25
Ramin	Least corrosive	5.25, 5.35
Obeche	Least corrosive	4.75, 6.75

REFERENCE TO TABLE 31.21

V. R. Gray, *J. Inst. Wood Sci.*, 1958, **1**, 58.

32 Electroplating and metal finishing

The processes and solutions described in this section are intended to give a general guide to surface finishing procedures. To operate these systems on an industrial scale would normally require recourse to one of the Chemical Supply Houses which retail properietary solutions. This particularly applies to electroplating baths containing brighteners.

32.1 Polishing compositions

The following abrasive powders are used for polishing metal.

ALOXITE

Aluminium oxide made by fusing bauxite. Used for cutting down in the same way as emery.

ALUMINA

Certain grades of alumina are used for polishing stainless steel and chromium. The material is generally used in the form of a composition in which the powder is mixed with stearines or other fats.

EMERY POWDER

Used principally in cutting down and for preliminary operations. It is applied to the mop by means of an adhesive, usually glue. Emery powder is an impure aluminium oxide containing about 50–60% Al_2O_3, 30–40% magnetite and small amounts of ferric oxide, silica, chromium, etc. Emery powder should never be used on magnesium or aluminium components because of the adverse effect on corrosion resistance.

TRIPOLI

A calcined diatomaceous earth used for polishing brass, steel and aluminium. It is used generally in the intermediate stages, and is usually compounded with stearines and paraffin wax to make a polishing composition which can be used directly on a mop.

CROCUS POWDER

A polishing composition consisting essentially of ferric oxide, of coarser grade than rouge, used for polishing iron and steel, and also, tin. Usually compounded with stearine and used with a mop or fibre brush.

ROUGE

A high-grade ferric oxide supplied in various degrees of fineness. It can be used in the form of a paste directly on to a soft mop or can be made into a composition with stearine. It is used essentially for finishing to obtain a very high polish on gold, silver, brass, aluminium, etc.

BLACK ROUGE

This consists of black oxide of iron and is sometimes used for finishing operations.

GREEN ROUGE

Chromic oxide used for polishing chromium and stainless steel and can be used either in the form of a composition mixed with stearine or as a paste applied directly to the mop.

VIENNA LIME

Used for making the white finish for polishing nickel, etc. It consists of a calcined dolomite and contains about 60% calcium oxide and 40% magnesia.

CARBORUNDUM

Silicon carbide used for low tensile strength materials, e.g. brass, copper, aluminium, etc. and also brittle metals, such as hard alloys and cast irons.

32.2 Cleaning and pickling processes

VAPOUR DEGREASING

Used to remove excess oil and grease. Components are suspended in a solvent vapour, such as tri- or tetrachloroethylene.
Note: Both vapours are toxic and care should be taken to ensure efficient condensation or extraction of vapours.

EMULSION CLEANING

An emulsion cleaner suitable for most metals can be prepared by diluting the mixture given below with a mixture of equal parts of white spirit and solvent naphtha.

Pine oil	62 g
Oleic acid	10.8 g
Triethanolamine	7.2 g
Ethylene glycol–monobutyl ether	20 g

This is used at room temperature and should be followed by thorough swilling.

Table 32.1 ALKALINE CLEANING SOLUTIONS

Metal to be cleaned	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
All common metals other than aluminium and zinc, but including magnesium	Sodium hydroxide (NaOH)	6	37.5	180–200	80–90	For heavy duty
	Sodium carbonate (Na_2CO_3)	4	25.0			
	Tribasic sodium phosphate ($Na_3PO_4 . 12H_2O$)	1	6.2			
	Wetting agent	$\frac{1}{4}$	1.5			

Table 32.1 ALKALINE CLEANING SOLUTIONS *–continued*

Metal to be cleaned	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
	Sodium hydroxide	2	12.5	180–200	80–90	For medium duty
	Sodium carbonate	4	25.0			
	Tribasic sodium phosphate	2	12.5			
	Sodium metasilicate ($Na_2SiO_3 . 5H_2O$)	2	12.5			
	Wetting agent	$\frac{1}{8}$	0.75			
	Tribasic sodium phosphate	4	25.0	180–200	80–90	For light duty
	Sodium metasilicate	4	25.0			
	Wetting agent	$\frac{1}{8}$	0.75			
Aluminium and zinc	Tribasic sodium phosphate	2	12.5	180–200	80–90	—
	Sodium metasilicate	4	25.0			
	Wetting agent	$\frac{1}{8}$	0.75			
Most common metals	Sodium carbonate	2	12.5	180–200	80–90	Electrolytic cleaner, 6 V Current density 100/A ft^{-2} (10/A dm^{-2}) Article to be cleaned may be made cathode or anode or both alternately
	Tribasic sodium phosphate	4	25.0			
	Wetting agent	$\frac{1}{4}$	1.5			
Most common metals	Sodium carbonate	6	37.5	Room	Room	May be used electrolytically
	Sodium hydroxide	1	6.25			
	Tribasic sodium phosphate	2	12.5			
	Sodium cyanide (NaCN)	2	12.5			
	Sodium metasilicate	1	6.25			
	Wetting agent	$\frac{1}{8}$	0.75			

Table 32.2 PICKLING SOLUTIONS

Metal to be pickled	*Composition of solution*			*Temperature*		*Remarks*
		oz gal^{-1}	g l^{-1}	°F	°C	
Aluminium (wrought)	*For etching* Sodium hydroxide (NaOH)	8	56	104–176	40–80	Articles dipped until they gas freely, then swilled, and dipped in nitric acid 1 part by vol. to 1 of water (room temperature)
Aluminium (cast and wrought)	Nitric acid, s.g. 1.42	1 gal	11	Room	Room	Articles first cleaned in solvent degreaser. Use polythene or PVC tanks
	Hydrofluoric acid (52%)	1 gal	11			
	Water	8 gal	81			

Note: It is almost universal practice to use an inhibitor in the pickling bath. This ensures dissolution of the scale with practically no attack on the metal. Inhibitors are usually of the long chain amine type and often proprietary materials. Examples are Galvene and Stannine made by ICI.

Table 32.2 PICKLING SOLUTIONS—*continued*

Metal to be pickled	*Composition of solution*	oz gal^{-1}	g l^{-1}	*Temperature* °F	°C	*Remarks*
	Bright dip					
	Chromic acid	0.84 oz	5.2 g	195	90	Immerse for $1\frac{1}{2}$ min.
	Ammonium bifluoride	0.72 oz	4.5 g			Solution has limited life.
	Cane syrup	0.68 oz	4.2 g			AR chemicals and
	Copper nitrate	0.04 oz	0.25 g			deionized or distilled
	Nitric acid (s.g. 1.4)	4.8 oz	30 ml			water should be used
	Water (distilled) to	1 gal	1 l			
Aluminium and other non-ferrous metals	*Bright dip*					
	Phosphoric acid (s.g. 1.69)	8.4 gal	9.41	195	90	Immerse for several min. Agitate work and solution. Good ventilation necessary. Addition of acetic acid useful with some alloys
	Nitric acid (s.g. 1.37)	0.6 gal	0.61			
Copper and copper alloys	*To remove scale*					
	Sulphuric acid*	1 gal	1 l	150–170	65–75	After pickling articles can be dipped in sodium cyanide: 4 oz gal^{-1} (25 g l^{-1}) to remove tarnish
	Water	4 gal	4 l			
	Or					
	Sulphuric acid*	1 gal	1 l	70–175	20–75	This solution leaves a slight passive film which helps to prevent tarnish
	Sodium dichromate ($Na_2Cr_2O_7 . 2H_2O$)	12 oz	75 g			
	Water	4 gal	4 l			
	Bright dip					
	Sulphuric acid*	2 gal	2 l	Room	Room	If any scale first dip in spent bright dip. Remove stains by dipping in sodium cyanide 4 oz gal^{-1} (25 g l^{-1})
	Nitric acid	1 gal	1 l			
	Water	1 gal	1 l			
	Hydrochloric acid	0.5 oz	25 ml			
	Matt dip					
	Sulphuric acid*	1 gal	1 l	160–180	70–80	If the finish is too fine add nitric acid. If too coarse add sulphuric acid
	Nitric acid (s.g. 1.42)	1 gal	1 l			
	Zinc oxide (ZnO)	2 lb	200 g			
	Semi-matt dip					
	Sodium dichromate	3 oz	19 g	Room	Room	
	Sulphuric acid*	18 oz	114 g			
	Water	1 gal	1 l			
Iron and steel	*Slow pickle to loosen heavy scale*					
	Sulphuric acid*	2%	—	Room	Room	Leave for several hours or overnight
	Glue	0.25%	—			
	To remove scale					
	Sulphuric acid*	10%	—	120–180	50–80	Or hydrochloric acid 10–20%

* Sulphuric acid, pure comcl. grade, s.g. 1.84.

Note: It is almost universal practice to use an inhibitor in the pickling bath. This ensures dissolution of the scale with practically no attack on the metal. Inhibitors are usually of the long chain amine type and often proprietary materials. Examples are Galvene and Stannine made by ICI.

Table 32.2 PICKLING SOLUTIONS—*continued*

Metal to be pickled	*Composition of solution*	oz gal^{-1}	g l^{-1}	*Temperature* °F	°C	*Remarks*
Iron and steel *continued*	*Bright dip*					
	Oxalic acid crystals	4 oz	25 g	Room	Room	This solution has so far only been used on an experimental basis
	Hydrogen peroxide (100 vol.)	2 oz	13 g			
	Sulphuric acid (10%)	0.02 oz	0.1 g			
	Water to	1 gal	1 l			
	Anode etching					
	Sulphuric acid*	1 gal	1 l	Not above 75	Not above 25	Current density: 200 A ft^{-2} (20 A dm^{-2})
	Water	2 gal	2 l			
	For polished work					
	Sulphuric acid*	—	—	Not above 75	Not above 25	Density must not fall below 1.61 g cm^{-3} or work will be etched
Magnesium and magnesium alloys	*General cleaner*					
	Chromic acid	16–32	100–200	Up to b.p.	Up to b.p.	For removal of oxide films, corrosion products, etc. Should not be used on oily or painted material
	Sulphuric acid pickle					
	Sulphuric acid*	3%	—	Room	Room	Should be used on rough castings or heavy sheet only. Removes approx. 0.002 in. in 20–30 s
	Nitro-sulphuric pickle					
	Nitric acid	8%	—	Room	Room	
	Sulphuric acid*	2%	—			
	Bright pickle for wrought products					
	Chromic acid	23	150	Room	Room	Lustrous appearance. Involves metal removal
	Sodium nitrate	4	25			
	Calcium or magnesium fluoride	$\frac{1}{8}$	$\frac{3}{4}$			
	Bright pickle for castings					
	Chromic acid	$37\frac{1}{2}$	235	Room	Room	
	Concentrated nitric acid (70%)	$3\frac{1}{4}$	20			
	Hydrofluoric acid (50%)	1	6.2			
	Acetic acid	8 approx.	50 approx.	Room	Room	Special purpose pickles
	Citric acid	8 approx.	50 approx.	Room	Room	Special purpose pickles

* Sulphuric acid, pure comcl. grade, s.g. 1.84.

Note It is almost universal practice to use an inhibitor in the pickling bath. This ensures dissolution of the scale with practically no attack on the metal. Inhibitors are usually of the long chain amine type and often proprietary materials. Examples are Galvene and Stannine made by ICI.

Table 32.2 PICKLING SOLUTIONS—*continued*

Metal to be pickled	*Composition of solution*	oz gal^{-1}	g l^{-1}	*Temperature* °F	°C	*Remarks*
Stainless steel	*To loosen scale*					
	Sulphuric acid*	13–30	80–180	130–160	60–70	Use prior to scale removal treatment, for heavy scales
	Hydrochloric acid (s.g. 1.16)	6–20	40–120			
	To remove scale					
	Nitric acid (s.g. 1.4)	32	200	130–150	55–65	
	Hydrofluoric acid (52% HF)	6	40			
	Or					
	Sulphuric acid*	10	60	Room	Room	
	Hydrofluoric acid	10	60			
	Chromic acid (CrO_3)	10	60			
	Bright pickle					
	Hydrochloric acid (s.g. 1.16)	40	250	140–160	60–70	
	Nitric acid (s.g. 1.4)	3	22			
	White matt finish					
	Ferric sulphate [$Fe_2(SO_4)_3$]	13	80	160–180	70–80	5–15 min
	Hydrofluoric acid (52% HF)	6	40			
Zinc and zinc alloys	*Bright dip*					
	Chromic acid (CrO_3)	40	250	Room	Room	5–30 s. If yellow film persists after rinsing dip in sulphuric acid: 1 fl oz per gal (6 ml l^{-1}) and rinse again
	Sodium sulphate (Na_2SO_4)	3	19			

* Sulphuric acid, pure comcl. grade, s.g. 1.84.

Note: It is almost universal practice to use an inhibitor in the pickling bath. This ensures dissolution of the scale with practically no attack on the metal. Inhibitors are usually of the long chain amine type and often proprietary materials. Examples are Galvene and Stannine made by ICI.

32.3 Anodizing and plating processes

Table 32.3 ANODIZING PROCESSES FOR ALUMINIUM
Good ventilation above the bath and agitation of the bath is advisable in all cases.

Composition of solution			*Temperature*		*Current density*	*Time and voltage*	*Cathodes*	*Vat*	*Hangers*	*Remarks*
	oz gal^{-1}	g l^{-1}	°F	°C	amp ft^{-2} (A dm^{-2})					
Chromic acid (CrO_3), chloride content must not exceed 0.2 g l^{-1}, sulphate less than 0.5 g l^{-1} (After Bengough-Stuart)	5–16	30–100	103–108	38–42	Current controlled by voltage. Average 3–4 (0.3–0.4) d.c.	†1–10 min 0–40 V increased in steps of 5 V 5–35 min Maintain at 40 V 3–5 min Increase gradually to 50 V 4–5 min Maintain at 50 V	Tank or stainless steel	Steel (exhaustcd)	Pure aluminium or titanium	Slight agitation is required This process cannot be used with alloys containing more than 5% copper
Sulphuric acid (s.g. 1.84)	32	200	60–75	15–24	10–20 (1–2) d.c.	12–18 V 20–40 min	Aluminium or lead plates (tank if lead lined)	Lead lined steel	Pure aluminium or titanium	The current must not exceed 0.2 A l^{-1} of electrolyte
Hard anodizing *Hardas process* Sulphuric acid	32	200	23–41	−5–+5	25–400 (2.5–40) d.c.	40–120 V	Lead	Lead lined steel	Aluminium or titanium	Agitation required. Gives coating 1–3 thou. thick
Eloxal GX process Oxalic acid $(COOH)_2.2H_2O$	12.8	80	70	20	10–20 (1–2) d.c.	50 V 30–60 min	Vat lining	Lead lined steel	Aluminium or titanium	Oxalic acid processes are more expensive than sulphuric acid anodizing; but coatings are thicker and are coloured.
Eloxal WX process Oxalic acid	12.8	80	75–95	25–35	20–30 (2–3) a.c.	20–60 V 40–60 min	Vat lining	Lead lined steel	Aluminium or titanium	
Integral colour Anodizing *Kalcolor process* Sulphuric acid Sulphosalicylic acid	0.8 16	5 100	72	22	30 (3) d.c.	25–60 V 20–45 min	Lead	Lead lined steel	Aluminium or titanium	Aluminium level in solution must be maintained between 1.5 and 3 g l^{-1}

† Period according to degree of protection. Complete cycle normally 40 min.

Table 32.4 ANODIZING PROCESSES FOR MAGNESIUM ALLOYS

Composition of solution			*Temperature*		*Current density*	*Time and voltage*	*Cathodes*	*Vat*	*Hangers*	*Remarks*
	oz gal^{-1}	g l^{-1}	°F	°C	A ft^{-2} (A dm^{-2})					
HAE process										
Potassium hydroxide	19.2	120	<95	<35	12–15 (1.2–1.5)	90 min at 85 V approx. a.c. preferred	Mg alloy for a.c. Mg or steel if d.c. used	Mild steel or rubber lined	Mg alloy	Matt hard, brittle, corrosion resistant, dark brown 25–50 μm thick, abrasion resistant
Aluminium	1.7	10.4								
Potassium fluoride	5.5	34								
Trisodium phosphate	5.5	34								
Potassium manganate	3.2	20								
Dow 17 process										
Ammonium bifluoride	39	232	160–180	70–85	5–50 (0.5–5)	10–100 min up to 110 V a.c. or d.c.	Mg alloy for a.c. Mg or steel for d.c.	Mild steel or rubber lined	Mg alloy	Matt dark green, corrosion resistant, 25 μm thick approx., abrasion resistant
Sodium dichromate	16	100								
Phosphoric acid 85% H_3PO_4	14	88								
Cr 22 process										
Chromic acid	4	25	165–205	75–95	15 (1.5)	12 min 380 V a.c.	—	Mild steel	Mg alloy	Matt dark green, corrosion resistant, 25 μm thick approx.
Hydrofluoric acid (50%)	4	25								
Phosphoric acid H_3PO_4 (85%)	13.5	84								
Ammonia solution	25–30	160–180								
MEL process										
Fluoride anodize										
Ammonium bifluoride	16	100	<86	<30	5–100 (0.5–10)	30 min 120 V a.c. preferred	Mg alloy for a.c. Mg or steel for d.c.	Rubber lined	Mg alloy	Principally a cleaning process to improve corrosive resistance by dissolving or ejecting cathodic particles from the surface

32.4 Electroplating processes

Table 32.5 PLATING PROCESSES

Metal	*Type and composition*	*Operating conditions*											*Remarks*
				Temperature		*Current density*		*Current efficiency*					
		oz gal^{-1}	g l^{-1}	°F	°C	A ft^{-3}	A dm^{-2}	%	*Voltage*	pH	*Anodes*	*Vat*	
Aluminium	Aluminium chloride Lithium aluminium hydride Diethyl ether	65 2 Solvent	400 13	60–140	15–60	20	2	100	—	—	Aluminium	Glass sealed	Operation must be in an atmosphere of nitrogen and the work introduced through a lock. Connections must not spark
Antimony	Antimony oxide (Sb_2O_3) Potassium citrate Citric acid	7 20 24	45 130 150	130	55	25	2.5	—	—	3.6	Antimony or carbon	Hard rubber or rubber lined	—
Brass	Sodium cyanide (NaCN) Copper cyanide (CuCN) Zinc cyanide ($Zn(CN)_2$) Sodium carbonate (Na_2CO_3) Ammonia (s.g. 0.88) Free cyanide	7.5 4 1.25 4 0.2* 2.6	45 26 7.7 26 1.5* 17	75–100	24–40	3–5	0.3–0.5	60–70 (cathode)	2–3	10.5–11.5	Brass (80/20) cast or rolled	Steel or rubber lined steel	*Brightener:* 2 lb caustic soda in $\frac{1}{2}$ gal of water to which is added 1 lb white arsenic. Use 2–4 fl oz gal^{-1} solution (15–30 ml per 100 l). Free cyanide by analysis
Bronze imitation	*Zinc* Sodium cyanide Copper cyanide Zinc cyanide Rochelle salt ($KNaC_4H_4O_6.4H_2O$) Free cyanide	5 4 0.3 2 0.3	33 26 2 13 2	Room for light colour, warm for red colour		2–4	0.2–0.4	—	2–3	—	Copper 92% Zinc 8%	Steel	—

* 0.2 fl oz gal^{-1} or 1.5 ml l^{-1}.

Table 32.5 PLATING PROCESSES—*continued*

Metal	*Type and composition*	*Operating conditions*										*Remarks*	
				Temperature		*Current density*		*Current efficiency*					
		oz gal^{-1}	g l^{-1}	°F	°C	A ft^{-2}	A dm^{-2}	%	*Voltage*	pH	*Anodes*	*Vat*	
Bronze imitation —*continued*	*Cadmium* Sodium cyanide Copper cyanide Cadmium oxide Sodium carbonate (Na_2CO_3) Free cyanide	4.5 3 0.25 2 1	29 20 1.5 13 6.5	Room		2–5	0.2–0.5	—	2–3	—	Copper	Steel	Cadmium content maintained by addition of small quantities of cadmium oxide dissolved in sodium cyanide
Bronze	Potassium cyanide Copper cyanide Potassium stannate (K_2SnO_3) Potassium hydroxide Rochelle salt Free cyanide	9 4 5 1.5 6 3	60 26 33 10 40 20	150	65	Up to 100	Up to 10	40–50	—	12.5	Copper	Steel	Must be kept free of bivalent tin. Maintain tin content by additions of potassium stannate
Cadmium	Sodium cyanide Cadmium oxide Free cyanide Addition agents	12–15 3–5 8–10 0.015–2.4	75–100 20–33 52–66 0.1–15	75–90	24–30	10–20	1–2	90	2–3	13	Cast cadmium or cadmium balls in a steel cage	—	*Brightener:* Organics (such as dextrin) or metallic (such as nickel salts)
Chromium	*Bright chrome* Chromic acid (CrO_3) Sulphuric acid	72 0.72	450 4.5	95–110	35–45	70–150	7–15	12–15	4–5	—	Tin (7%) lead	Steel lined with antimonial lead 7% or PVC	This solution requires reducing: either boil with citric acid 2 oz gal^{-1} (12.5 g l^{-1}) or with tartaric acid 3 oz gal^{-1} (18 g l^{-1}) or with oxalic acid 4 oz gal^{-1} (25 g l^{-1})
	Hard chrome Chromic acid Sulphuric acid	40 0.4	250 2.5	120–140	50–60	200–700	20–70	12	5–7	—	Tin (7%) lead	Steel lined with antimonial lead 7% or PVC	Reduction as above: citric acid 1 oz gal^{-1} (6.25 g l^{-1}) or tartaric acid 1½ oz gal^{-1} (9 g l^{-1}) or oxalic acid 2 oz gal^{-1} (12.5 g l^{-1})

	Black chrome												
	Chromic acid	33	220	90	30	150–450	15–45	—	—	—	Tin (7%) lead	Steel lined with antimonial lead (7%) or PVC	Before use, work solution on scrap plates until 100–150 A h per gal, has been passed
	Fluosilicic acid	0.033	0.22										
Copper	*Acid*												
	Copper sulphate ($CuSO_4 . 5H_2O$)	32	200	60–120	16–50	10–200	1–20	95–97	1–3	—	Pure copper	Lead or rubber lined wood or steel	The phenol is sulphonated by heating with its own weight of sulphuric acid to 120°C for 1 h before use. Agitation is necessary for high current density. Constant filtration is advisable
	Sulphuric acid	8.0	50										
	Phenol	0.16	1										
	Through-hole plating												
	Copper sulphate	14–17	88–110	75–90	24–30	10–45	1–45	—	—	—	Copper	Lead or rubber lined steel	Chloride content serves as a deposit modifier
	Sulphuric acid	27–30	170–190										
	Chloride	> 15 ppm											
	Cyanide (strike)												
	Sodium cyanide (NaCN)	3	19	110–140	45–60	10–30	1–3	10–60	6	11–12	Pure copper rolled or extruded	Steel	Used to deposit thin undercoats for other metals
	Copper cyanide (CuCN)	2	13										
	Sodium carbonate (Na_2CO_3)	2	13										
	Cyanide (high efficiency)												
	Sodium cyanide	13	82	140–180	60–80	10–100	1–10	100	2–4	—	Oxide-free copper sheet	Steel	For rapid plating
	Copper cyanide	10	60										
	Sodium hydroxide	4	26										
	Cyanide (Rochelle)												
	Sodium cyanide	6	37.5	125–160	50–70	20–60	2–6	50–60	6	12.2–12.8	Copper, rolled and annealed	Steel	—
	Copper cyanide	4	26										
	Rochelle salt ($KNaC_4H_4O_6 . 4H_2O$)	8	50										
	Sodium carbonate	5	30										
	Free cyanide	0.5–1	3–6										

Table 32.5 PLATING PROCESSES—*continued*

Metal	*Type and composition*	*Operating conditions*										*Remarks*
				Temperature		*Current density*		*Current efficiency*				
		oz gal^{-1}	g l^{-1}	°F	°C	A ft^{-2}	A dm^{-2}	%	*Voltage*	pH	*Anodes*	*Vat*
Copper —*continued*	*Pyrophosphate*											
	Copper pyrophosphate ($Cu_2P_2O_7.3H_2O$)	11	66	125–140	50–60	10–80	1–8	100	—	8–8.8	Copper	Steel
	Potassium pyrophosphate	45	300									
	Ammonium nitrate	1	6									
	Ammonia	0.1	0.6									
Gold	*Hard*											
	Potassium gold cyanide ($KAu(CN)_2$)	2	12	97	35	5–15	0.5–1.5	—	—	3–4.5	Insoluble	—
	Citric acid	16	105									
	Phosphoric acid	2	12.5 ml									
	Cobalt (as CoK_2EDTA)	0.16	1									
	Alkaline cyanide											
	Potassium cyanide	5	30	120–150	50–65	1–5	0.1–0.5	100	1.5–2	11	Fine gold (24-carat) or insoluble: stainless steel, platinum or graphite	Enamelled iron
	Potassium gold cyanide	2	12									
	Potassium carbonate	5	30									
	Dipotassium phosphate (K_2HPO_4)	5	30									
Indium	(1) Indium fluoborate	38	230	70–90	20–30	50–100	5–10	75	—	1	Part indium, part insoluble	—
	Boric acid	4.8	30									
	Ammonium fluoborate	7.5	47									
	(2) Indium (as hydroxide)	2.5–5	15–30	70–90	20–30	15–30	1.5–3	50	—	11–12	Steel	—
	Potassium cyanide	22–25	140–160									
	Potassium hydroxide	5–6	30–40									
	D-glucose	3–5	20–30									
Iron	Ferrous chloride ($FeCl_2.4H_2O$)	48	300	195	90	Up to 120	Up to 12	—	—	1.2–1.8	Pure iron	Lead or rubber lined
	Calcium chloride	50	335									

Remarks
Commonly used for plating printed circuit boards. Use vigorous agitation
—
If insoluble anodes are used, solution must be renewed periodically
Use fluoboric acid to adjust pH
—
Agitation is desirable for high current densities

Lead	Lead fluoborate ($Pb(BF_4)_2$)	40	240	77–100	25–40	5–70	0.5–7	100	—	—	Pure lead free from antimony	Rubber lined steel	—
	Fluoboric acid	10	60										
	Boric acid (H_3BO_3) free	4.5	27										
	Glue	0.03	0.2										
Nickel	*Watts bath*												
	Nickel sulphate ($NiSO_4.6H_2O$)	50	350	110–150	45–65	50	5	95	—	3–4	Cast or rolled Ni (99–100%) bagged	Lead or rubber lined	Agitation desirable for high current densities. Constant filtration desirable. *Wetting agent*. Sod, lauryl sulphate
	Nickel chloride ($NiCl_2.6H_2O$)	7	45										
	Boric acid	6	37										
	Wetting agent	0.015–0.075	0.1–0.5										
	For plating zinc and zinc-base alloys												
	Nickel sulphate	12–17	75–112	70–90	20–32	10–30	1–3	—	3–4	5.3–5.8	Nickel (99–100%)	Lead or rubber lined	Agitation can be used
	Sodium sulphate (anhydrous)	12–17	75–112										
	Ammonium chloride	2.4–6	15–37.5										
	Boric acid	2.4	15										
	Sulphamate bath												
	Nickel sulphamate ($Ni(NH_2SO_3)_2$)	48	300	80–140	25–60	20–250	2–25	—	—	3.5–4.2	Nickel (99–100%)	Lead or rubber lined	Air or mechanical agitation
	Boric acid	4.8	30										
	Nickel chloride	1	6										
	Hard nickel												
	Nickel sulphate	28	180	110–140	43–60	20–100	2–10	—	6–8	5.6–5.9	Nickel (99–100%)	—	For building up worn parts
	Ammonium chloride	4	25										
	Boric acid	4.8	30										
	(*1*) *Bright*												
	Nickel sulphate	50	330	110–150	45–65	25–100	2.5–10	95	—	3–4	Nickel (99–100%)	Rubber lined steel	Bright nickel plating baths are basically Watts solutions containing brighteners
	Nickel chloride	7	45										
	Boric acid	6	38										
	Sodium naphthalene trisulphonate ($C_{10}H_7(SO_3)_3Na$)	5.6	35										
	(*2*) *Bright (low metal)*												
	Nickel sulphate	9.6	60	97–140	35–60	25–100	2.5–10	95	—	3.5–4.2	Nickel	Rubber lined steel	Agitation constant filtration necessary
	Nickel chloride	18	110										
	Boric acid	8	50										

Table 32.5 PLATING PROCESSES—*continued*

		Operating conditions											
				Temperature		*Current density*		*Current efficiency*					
Metal	*Type and composition*	oz gal^{-1}	g l^{-1}	°F	°C	A ft^{-3}	A dm^{-2}	%	*Voltage*	pH	*Anodes*	*Vat*	*Remarks*
Nickel —*continued*	*Woods nickel strike bath*												
	Nickel chloride	38	240	70–80	21–27	30	3	—	—	—	Nickel	Rubber lined or plastic	Used to strike onto metals such as stainless steel or nickel. Pre-etch in bath at 3 A dm^{-2} anodic for 2 min before strike plating for 6 min
	Hydrochloric acid	13	80										
	Black or grey												
	Nickel chloride	12	75	Room		1.5	0.15	—	—	5	Nickel or insoluble	Rubber lined	—
	Ammonium chloride	4.8	30	temperature									
	Zinc chloride	4.8	30										
	Sodium thiocyanate (NaCNS)	2.4	15										
Palladium	Palladium (as $Pd(NH_3)_4Br_2$)	4.8	30	120	50	40	4	—	—	9.2	Insoluble	Glass or rubber lined	Can be used to produce thick deposits for electro forming
	Ammonium bromide	7	45										
Platinum	Platinum (as dinitrodiamino platinum)	1.6	10	203	95	70	7	10	2–4	—	Platinum or insoluble	Glass or rubber lined	Solution maintained by addition of platinum salt
	Ammonium nitrate	16	100										
	Sodium nitrite	1.6	10										
	Ammonia (s.g. 0.88)	7*	44†										
Rhodium	Rhodium (as sulphate concentrate)	0.32	2	104	40	10–40	1–4	—	3–6	—	Platinum or insoluble	Glass or rubber lined	During plating remove bubbles by cathode agitation
	Sulphuric acid	3.2†	20‡										
Silver	Potassium cyanide	8–12	50–78	70–80	20–27	5–15	0.5–1.5	99–100	<1	—	Fine silver rolled	Lead or rubber lined	Cathode bar may be rocked. *Brightener:* Carbon bisulphide dissolved in silver solution
	Silver cyanide (80%Ag)	5–9	31–56										
	Potassium carbonate	2.5–14	15–90										
	Free cyanide	5.5–8	35–50										

	High speed												
	Silver cyanide (80%)	7–25	44–150	100–120	38–50	5–100	0.5–10	--	—	12	Pure silver (bagged)	Enamelled iron or rubber lined	Agitation is necessary and is usually effected by solution pumping or cathode movement. Constant filtration advisable
	Potassium cyanide (92%)	11–38	70–240										
	Caustic soda	0.6–4.8	4–30										
	Potassium carbonate	2.5–14	15–90										
	Potassium nitrate	6.4–9.6	40–60										
	Strike solution for non-ferrous metals												
	Silver cyanide	0.7	4.5	Room temperature		15–20	1.5–2.0	—	4–6	—	Silver or steel	Steel or earthenware	—
	Potassium cyanide	13	80										
Tin	*Acid*												
	Sulphuric acid	8	50	68	20	10–100	1–10	~100	9.4–0.8	—	Pure tin bagged in terylene	Lead or rubber lined	Constant filtration advantageous. Periodic filtration essential. Use agitation at higher current densities
	Cresol sulphonic acid ($CH_3.C_6H_3OH.SO_3H$)	6.4	40										
	Stannous sulphate (90% $SnSO_4$)	10	65										
	Gelatin	0.3	2										
	Beta-naphthol	0.16	1										
	Alkaline												
	Caustic soda	1.6	10	167	75	5–30	0.5–3	85	4–6	13	Pure tin (high speed 1% Al) or insoluble	Steel	Anode must be filmed for uniform dissolution
	Sodium stannate (48% SnO_2)	16	100										
	Immersion (on steel)												
	Stannous sulphate	0.16–0.32	1–2	200–232	90–100	--	—	—	—	—	—	—	Immersion time 5–20 min, work immersed in Monel or stainless steel baskets
	Sulphuric acid	0.8–2.5	5–15										
Tin–nickel	Stannous chloride ($SnCl_2$)	8	50	154	68	10–30	1–3	100	2–3	2–2.5	Nickel	Rubber lined	Tin content maintained by regular additions of anhydrous stannous chloride
	Nickel chloride	48	300										
	Ammonium bifluoride ($NH_4F.HF$)	9	56										
Tin–lead	Tin (as fluoborate)	4	25	68–86	20–30	5–35	0.5–3.5	95	6–12	—	60/40 tin/lead alloy	Rubber lined	This process gives a 60/40 tin/lead deposit. Proprietary grain refiners are available to replace peptone
	Lead (as fluoborate)	2	12										
	Fluoboric acid	16	100										
	Peptone	0.8	4.5										
	Boric acid	5	30										

* 7 fl oz gal^{-1} or 44 ml l^{-1}. † 3.2 fl oz gal^{-1} or 20 ml l^{-1}.

Table 32.5 PLATING PROCESSES — *continued*

Metal	*Type and composition*	*Operating conditions*											*Remarks*
				Temperature		*Current density*		*Current efficiency*					
		oz gal^{-1}	g l^{-1}	°F	°C	A ft^{-3}	A dm^{-2}	%	*Voltage*	pH	*Anodes*	*Vat*	
Zinc	*Acid*												
	Zinc chloride ($ZnCl_2$)	10	60	68–100	20–40	5–50	0.5–5	95	3–8	4.5–5.5	Zinc (99.9%)	Lead or rubber lined	Agitation and constant filtration necessary for high current densities
	Potassium chloride	25	150										
	Boric acid	3.7	23										
	Proprietary organic additives	3.2–8*	20–50*										
	Cyanide (decorative)												
	Sodium cyanide	8–22	50–140	68–120	20–50	25–150	2.5–15	~85	—	—	Pure zinc	Steel	—
	Caustic soda	10–20	60–120										
	Zinc oxide (ZnO)	4–9	25–55										
	Sodium carbonate	3.2–20	20–120										
	Cyanide (protective)												
	Sodium cyanide	15–25	90–150	68–120	20–50	25–150	2.5–15	—	—	—	Pure zinc free from lead	Steel	—
	Caustic soda	15–22	90–140										
	Zinc oxide	9–12	55–75										
	Sodium carbonate	5–12	30–75										
	Zincating (on aluminium)												
	Caustic soda	80	500	77	25	—	—	—	—	—	—	—	Improved adhesion by zincating, stripping in 40% HNO_3 and rezincating
	Zinc oxide	16	100										

* 3.2–8 fl oz gal^{-1} or 20–50 ml l^{-1}.

32.5 Plating processes for magnesium alloys

DOW PROCESS (H. K. DELONG)

This process depends on the formation of a zinc immersion coat in a bath of the following composition:

Component	*Concentration* oz gal^{-1}	g l^{-1}
Tetrasodium pyrophosphate	16	120
Zinc sulphate	5.3	40
Potassium fluoride	1.0	7

The treatment time is 3–5 min at a temperature of 175–185 °F (80–85 °C) with mild agitation. The pH of the bath should be 10–10.4.

The steps of the complete process are:

1. Solvent or vapour degreasing.
2. Hot caustic soda clean or cathodic cleaning in alkaline cleaner.
3. Pickle $\frac{1}{4}$–$1\frac{1}{2}$ min in 1% hydrochloric acid and rinse.
4. Zinc immersion bath as above without drying off from the rinse.
5. Cold rinse and immediately apply copper strike as under.

Component	*Concentration* oz gal^{-1}	g l^{-1}
Copper cyanide	4.2	26
Potassium cyanide	7.4	46
Potassium carbonate	2.4	15
Potassium hydroxide	1.2	7.5
Potassium fluoride	4.8	30
Free cyanide	1.2	7.5
pH	12.8–13.2	—
Temperature	140 °F (60 °C)	—

CONDITIONS

30–40 A ft^{-2} (3–4 A dm^{-2}) for $\frac{1}{2}$–1 min, reducing to 15–20 A ft^{-2} (1.5–2 A dm^{-2}) for 5 min or longer.

If required, the copper thickness from the above strike can be built up in the usual alkaline or proprietary bright plating baths. Following the above steps, further plating may be carried out in conventional electroplating baths.

ELECTROLESS PLATING ON MAGNESIUM

Deposits of a compound of nickel and phosphorus can be obtained on magnesium alloy components by direct immersion in baths of suitable compositions. Details of the process may be obtained from the inventors, The Dow Chemical Co. Inc., Midland, Michigan, USA.

'GAS PLATING' OF MAGNESIUM (VAPOUR PLATING)

Deposits of various metals on magnesium components (as on other metals) can be produced by heating the article in an atmosphere of a carbonyl or hydride of the metal in question.

32.6 Electroplating process parameters

Table 32.6 AVERAGE CURRENT EFFICIENCIES OF PLATING SOLUTIONS
The figures given below are approximate

	%
Cadmium (oxide)	85–95
Chromium	12–16
Copper (acid)	95–99
Copper (cyanide)	30–60
Copper (Rochelle)	40–65
Gold	70–85
Indium (cyanide)	30–50
Indium (sulphate)	70–90
Iron	90–95
Lead	90–100
Nickel	94–98
Silver	100
Tin (acid)	90–95
Tin (stannate)	70–85
Rhodium	35–40
Zinc (acid)	97–99
Zinc (cyanide)	85–90

Thickness of metal deposited per hour is given in mils (1 mil = 0.001 in) by

$$\frac{CD \times W \times CE}{237 \times \Delta}$$

where

CD = current density in A ft^{-2}
W = g A^{-1} h (Table 32.7)
CE = current efficiency (Table 32.6)
Δ = density of metal deposited

Table 32.7 THEORETICAL RELATIONS OF METAL AND CURRENT

	Metal deposited		*Current required*	
Metal	g A^{-1} h	oz A^{-1} h	A h lb^{-1}	A h kg^{-1}
Aluminium	0.335	0.011 8	1 356	2 989
Antimony (antimonious)	1.515	0.053 4	299	659
Cadmium	2.096	0.073 9	216	476
Chromium (hexavalent)	0.323 5	0.011 4	701	1 545
Cobalt	1.099	0.038 8	413	911
Copper (cuprous)	2.372	0.083 7	191	421
Copper (cupric)	1.186	0.041 8	383	844
Gold (auric)	2.452	0.086 5	185	408
Indium	1.428	0.050 3	318	701
Iron (ferrous)	1.042	0.036 8	435	959
Lead	3.866	0.136 3	117	258
Nickel	1.095	0.038 6	414	913
Palladium	1.990	0.070 2	228	503
Platinum	3.642	0.128 4	125	276
Rhodium	1.920	0.067 7	236	520
Silver	4.025	0.129 4 (Troy)	113 (Avoir.)	350
Tin (stannous)	2.215	0.078 1	205	451
Tin (stannic)	1.108	0.039 1	409	902
Zinc	1.220	0.043 0	372	820

32.7 Miscellaneous coating processes

(1) AUTOCATALYTIC PLATING

Autocatalytic plating is a form of electroless plating in which metal is deposited via a chemical reduction process (as opposed to immersion plating in which thin coatings are formed by electrochemical displacement of the coating metal).

Processes exist for the autocatalytic deposition of a large number of metals, particularly nickel, gold, silver and copper. Basically, the solutions contain a salt of the metal to be deposited and a suitable reducing agent (most commonly hypophosphite, but also hydrazine and boranes etc.). When a metal substrate, which is catalytic to the solution, is introduced into the bath, it becomes covered with a layer of the coating metal which is itself catalytic and thus the process can continue. This mechanism results in an extremely even distribution of deposit on the substrate, i.e. these solutions have a high 'throwing power'.

The most widely used autocatalytic process is nickel–phosphorus; a typical acid bath is as follows:

nickel chloride	4.8 oz gal^{-1}	(30 g l^{-1})
sodium hypophosphite	1.6 oz gal^{-1}	(10 g l^{-1})
sodium glycollate	8.0 oz gal^{-1}	(50 g l^{-1})

The solution is operated at temperatures between 75 and 100°C, at pH 4–6, giving deposition rates up to 0.6 thou per hour (15 $\mu m\ h^{-1}$). The deposit is an alloy of nickel and phosphorus, containing about 7–10% phosphorus. A useful property of this material is that it can be hardened (typically by heat treating for 1 hour at 400°C) so as to increase the as-deposited hardness from 400 HV to almost 1 000 HV. Thus, autocatalytic nickel coatings find engineering applications, often as a replacement for hard chromium electrodeposits.

(2) COMPOSITE COATINGS

Composite coatings can be electroplated or electroless plated deposits into which a uniform distribution of a second phase material is dispersed. The incorporated material can be hard, ceramic particles for increased wear resistance, as in the Tribomet process carried out by BAJ Ltd. Alternatively, PTFE particles can be used to increase surface lubricity as in the Niflor process from Norman Hay Engineered Surfaces Ltd.

(3) ELECTROSTATIC AND ELECTROPHORETIC METHODS OF PAINT APPLICATION

These are methods which have been developed for the economic application of paint to articles of complicated shapes (and often skeleton structure) in large numbers.

When an article like a metal chair is sprayed by a conventional spray gun procedure, much of the spray overshoots the surfaces and is wasted. In the electrostatic method a very high electrical potential is developed between the gun and the article being painted. The droplets of paint assume a charge of opposite sign to the workpiece and are attracted to it. This ensures more uniform coverage, less overspray, and thus greater economy in operation.

Electrophoresis has been utilized in a somewhat similar way. When a direct current is applied to an aqueous emulsion, large dispersed molecules and even oily particles are caused to move towards one of the electrodes. In the electrophoretic process a paint is provided as an aqueous emulsion and current is applied in such a manner that the globules of paint move towards and attach themselves to the object to be painted. The process can be made automatic and continuous and results in very uniform build-up even on points and sharp edges. It is only suitable for large-scale operations but is very economical in paint.

(4) COATING WITH CERAMIC MATERIALS

Just as metals can be sprayed, certain refractory oxides and silicates and the like can be applied by flame gun. Coating thickness and uniformity can be controlled by suitable means and hard, dense coatings can be built up. The coatings resemble biscuit-ware rather than a vitreous glaze, that is, they are absorbent: their chief use is to provide abrasion resistance and to delay heat transfer.

(5) MECHANICAL PLATING

Mechanical plating is a method of plating which utilizes mechanical energy to deposit metal coatings on to metal parts. Parts, glass beads, water, chemicals and metal powder are tumbled together in a barrel at around room temperature to obtain the desired coating.

The process is used primarily to provide ferrous-based parts with sacrificial coatings of zinc, cadmium, and co-deposits with tin. Parts treated by this method are most often fasteners, springs, clips and sintered iron components which are typically handled in bulk.

Parts which have been degreased, descaled, and copper-flashed are tumbled in rubber-lined barrels with water, glass bead impact media, promoter chemicals. and a finely divided powder of the metal to be plated. The promoter chemical serves to clean the metal powder and controls the size of the metal powder agglomerates that are formed. The mechanical energy generated from the barrel's rotation is transmitted through the glass impact media and causes the clean metal powder to be cold welded to the clean metal parts, thereby providing an adherent, metallic coating.

Due to the absence of an impressed current during coating, the process does not produce hydrogen diffusion into the steel substrate. Thus, a post-electroplating bake, in order to preclude hydrogen embrittlement of high strength steel components, is not required for mechanically plated deposits.

32.8 Plating formulae for non-conducting surfaces

(1) METAL POWDERS

The article to be treated may be coated with a metal powder. The best powder for this purpose is a finely ground copper, which is generally sold under the commercial title of bronze powder. This may be applied by mixing it with a cellulose lacquer to which has been added five parts by volume of thinner and spraying it on the object concerned. Alternatively, the object may first be sprayed with lacquer and before it is quite dry may be brushed over with the bronze powder using a soft camel-hair brush. After this treatment the article can be struck over in an acid copper solution.

Waxes (for gramophone records, etc.) may be coated directly by brushing with bronze powder and a soft brush. After brushing with bronze powder they may be treated in the following manner to improve the conductivity and reduce the time of covering in the plating bath:

1. Brush with a soft brush and a 50% mixture of methylated spirit and distilled water.
2. Immerse in a solution containing 30 g l^{-1} of sodium cyanide and 6 g l^{-1} of silver nitrate.
3. Make up two solutions as follows: (a) Pyrogallic acid 7 g l^{-1}, citric acid 4 g l^{-1} and (b) silver nitrate, 40 g l^{-1}. Take four parts of solution (a) and one part of solution (b) and mix together and immerse article in this solution for about 10 min.
4. Swill and place in plating bath.

(2) SILVER REDUCTION

A number of articles can be treated by directly reducing silver on the surface. This process is particularly applicable to plastics and glass. Any process which will form a good silver mirror may be used, but the following will be found satisfactory for most purposes.

1. The surface of the article must be very thoroughly cleaned and completely free from grease. Glass and porcelain may be cleaned by using concentrated acid and alkali alternately. Plastics may be treated by brushing or barrelling with a mixture of Vienna lime and pumice, by treating with a suitable solvent or by immersing in a solution of chromic acid.
2. Priming. After cleaning the article is immersed in a 10% stannous chloride solution. Alternately, the solution may be swabbed on to the surface with cotton wool. The article is then thoroughly swilled.
3. The article is then silvered by immersing in a silvering solution, the formula for which is given below. The silvering operation generally takes about 20 min and the temperature must be carefully controlled during this period; usually about 21 °C will be found the most satisfactory. The solution should be slightly agitated during the process.
4. The articles are thoroughly swilled and struck over in a copper tartrate bath. After being coated over with copper any desired plating can be made upon it.

The silvering solution is prepared from the following:

Solution (a) 100 g l^{-1} Rochelle salt.
Solution (b) 10 g l^{-1} silver nitrate.
Solution (c) 200 cm^3 per litre ammonia (sp. gr. 0.880).

Take 100 cm^3 of solution (b) and add solution (c) carefully a little at a time until the precipitate which first forms just redissolves. If too much is added and the solution becomes quite clear, add a few drops of solution (b) until a very faint turbidity is produced. Then add 20 cm^3 of solution (a), thoroughly mix and use immediately.

[N.B. The brown precipitate formed by adding ammonia to silver nitrate is explosive if allowed to dry. Care should be taken therefore to see that this does not happen.]

(3) 'VACUUM METALLIZING'

This process is carried out at less than 0.0007 mmHg pressure and can only be applied to objects which are stable under these conditions. The metal to be deposited is heated until it evaporates and there are several ways in which this is achieved. The vapour recondenses on the first cool surface it encounters, and can be made to form a thick dense coating. The 'throwing power' is very poor since the evaporated metal travels in straight lines and steps must be taken to rotate or manipulate objects exposed to it in order to achieve uniform coating. By controlling the temperature of the work piece the crystal structure of the deposit can be varied.

32.9 Methods of stripping electroplated coatings

CADMIUM OR TIN FROM STEEL

Coatings may be stripped from steel by immersing the article in a solution containing 1 gal (4.5 litres) of hydrochloric acid, 2 oz (57 g) of antimony trioxide and $\frac{1}{2}$ pint (280 ml) of water. After stripping and rinsing the article will probably require wiping to remove smuts.

CHROMIUM

Chromium may be stripped from non-ferrous metals by dissolving it in dilute hydrochloric acid. From steel it is best stripped by making it the anode in a solution of sodium hydroxide. If the base metal is zinc or zinc base diecastings, it is best to strip the chromium by making it the anode in sodium carbonate solution as this will not attack the exposed zinc. The conditions of operation are not critical.

COPPER FROM STEEL

Copper can be stripped from steel by immersing in a solution containing 5 lb gal^{-1} (500 g l^{-1}) of chromic acid and 8 oz gal^{-1} (50 g l^{-1}) of sulphuric acid. This solution will work at room temperature but strips the copper very quickly if heated.

Alternatively, the article can be made anodic (2–6 V) in a solution containing 14 oz gal^{-1} (90 g l^{-1}) sodium cyanide and 2.4 oz gal^{-1} (15 g l^{-1}) sodium hydroxide.

COPPER FROM ZINC AND ZINC BASE DIECASTINGS

Copper may be stripped from these materials by immersing in a solution prepared by dissolving 18 g of sulphur and 250 g of sodium sulphide ($Na_2S.9H_2O$) in a litre of solution. The solution works very rapidly if warmed. The sludge formed on the surface of the object will require removing from time to time by brushing or immersion in a 120 g l^{-1} sodium cyanide solution.

COPPER, NICKEL, ETC., FROM MAGNESIUM

Most metal deposits can be removed from plated magnesium by submitting the component to the fluoride anodizing process. Alternating current is used in a bath of 10% ammonium bifluoride, in which the plating gradually dissolves without affecting the magnesium. About 4–10 V are used until most of the plating has disappeared. Finally, the voltage is raised to 120 V to complete the process and cleanse the magnesium from remaining traces of foreign metal. Magnesium hangers must be used with firm connections. The bath should be operated cold. Direct current may be used if the work piece is made the anode using mild steel or magnesium cathodes.

LEAD FROM STEEL, COPPER AND BRASS

Immersion of article in a solution of 95 vol. % glacial acetic acid, 5 vol. % hydrogen peroxide (30 wt %). Dilute solutions may be used although this can lead to pitting of steel.

NICKEL FROM COPPER AND BRASS

Nickel may be stripped from copper by an anodic treatment in either 60 vol. % sulphuric acid or 15 g l^{-1} hydrochloric acid. Care must be taken with the concentration of the acids as this can affect the pitting of the substrates.

NICKEL FROM STEEL

Nickel can be anodically stripped in sulphuric acid, as for nickel from copper. Copper sulphate (30 g l^{-1}) or glycerine (30 g l^{-1}) can be added to reduce pitting of the steel. An immersion process involves the use of fuming nitric acid (85–95% HNO_3, sp. gr. 1.50) from which water is excluded.

SILVER FROM BRASS

Silver may be stripped from brass by immersing the object in a mixture of 1 vol. conc. nitric acid and 19 vols. conc. sulphuric acid heated to 175 °F (80 °C). The silver is dissolved in a few minutes. The articles should be immediately removed and swilled.

ZINC FROM STEEL

The reagent used for stripping cadmium may be used. Alternatively zinc may be stripped from steel in either warm dilute hydrochloric or sulphuric acid, or 10–15% ammonium nitrate solution, or hot sodium hydroxide solution.

32.10 Conversion coating processes

(I) PHOSPHATING

Phosphating solutions are used to produce corrosion-resistant coatings on ferrous metals and also zinc, cadmium and aluminium. Probably the most important application for these coatings is to act as bases for subsequent painting operations.

Basically, phosphate solutions comprise metal phosphates dissolved in carefully balanced solutions of phosphoric acid. When a clean metal surface is dipped into the solution, the free acid present reacts with the metal, liberating hydrogen and causing the pH of the solution, adjacent to the metal, to rise. This unbalances the solution, resulting in the precipitation of metal phosphates which form a film, chemically bonded to the substrate.

Due to the complexity of modern phosphate solutions, these processes are normally proprietary, examples of which are listed in section 32.11.

There are four main types of phosphate solution: iron, zinc, heavy zinc and manganese, and these produce increasing weights of coating from 30–90 mg ft^{-2} for iron phosphate solutions to 1000–4000 mg ft^{-2} for manganese phosphate solutions.

(2) CHROMATING

Chromating solutions contain hexavalent chromium ions and a mineral acid and are used to increase the corrosion resistance of metals, in particular zinc, cadmium, aluminium and magnesium, by forming a surface layer containing chromium compounds.

The process is usually performed by immersion, although spraying or brushing processes are also used. A wide variety of proprictary solutions are available which produce coatings of different thicknesses. These coatings are often distinguishable by their colour which can vary from clear, to blue, to iridescent yellow and finally to black.

(3) COLOURING OF METALS

The following solutions and operating conditions will produce coloured conversion coatings, as detailed:

(i) Copper and Brass

Black

Copper carbonate	1 lb (454 g)
Ammonia	2 pt (950 ml)
Water	5 pt (2.4 l)

The copper carbonate and ammonia are mixed before adding the water. The solution is operated at 175°F (80°C).

The blue black colour may be fixed by dipping in $2\frac{1}{2}\%$ sodium hydroxide solution.

Green

Water	1 gal (USA)	(3.8 l)
Sodium thiosulphate	8 oz	(227g)
Nickel ammonium sulphate	8 oz	(227 g)
or Ferric nitrate	1 oz	(28 g)
Temperature	160°F	(71°C)

Brown

Potassium chlorate	$5\frac{1}{2}$ oz	(154 g)
Nickel sulphate	$2\frac{3}{4}$ oz	(77 g)
Copper sulphate	24 oz	(680 g)
Water	1 gal (USA)	(3.8 l)
Temperature	195–212°F	(90–100°C)

(ii) Iron and steel

Black

Sodium hydroxide	8 lb	(3.6 kg)
Sodium nitrate	$1\frac{1}{2}$ oz	(42 g)
Sodium dichromate	$1\frac{1}{2}$ oz.	(42 g)
Water	1 gal.	(3.8 l)
Temperature	295°F	(146°C)

Blue

Ferric chloride	2 oz	(56 g)
Mercuric nitrate	2 oz	(56 g)
Hydrochloric acid	2 oz	(56 g)
Alcohol	8 oz	(227 g)
Water	8 oz	(227 g)

Room temperature. Parts are immersed for 20 minutes, removed and allowed to stand in air for 12 hours. Repeat and then boil in water for 1 hour. Dry, scratch-brush and oil.

Brown

Copper sulphate	3 oz gal^{-1}	(20 g l^{-1})
Mercuric chloride	0.8 oz gal^{-1}	(5 g l^{-1})
Ferric chloride	5 oz gal^{-1}	(30 g l^{-1})
Nitric acid	25 oz gal^{-1}	(150 g l^{-1})
Alcohol	93 fl oz gal^{-1}	(700 ml l^{-1})

Dip in solution, place in hot box at 175 °F (80 °C) for 30 minutes, stand in steam box at 150 °F (65 °C) until coated in red rust, immerse in boiling water to form black oxide, dry and scratch brush. Repeat this operation three times before oiling with linseed oil.

(iii) Stainless steel

Black

Sulphuric acid	180 parts	
Water	200 parts	
Potassium dichromate	50 parts	
Temperature	210 °F (99 °C)	

(iv) Zinc

Black

Ammonium molybdate	4 oz gal^{-1}	(24 g l^{-1})
Ammonia	6 fl oz gal^{-1}	(45 ml l^{-1})

Heat solution to obtain a deep black. Rinse in cold and then hot water; allow to dry and harden.

(v) Aluminium

Black

Potassium permanganate	1.6 oz gal^{-1}	(10 g l^{-1})
Nitric acid	0.5 fl oz gal^{-1}	(4 ml l^{-1})
Copper nitrate	4 oz gal^{-1}	(25 g l^{-1})

Operate at 70 °F (24 °C) for 10 minutes.

Blue

Ferric chloride	60 oz gal^{-1}	(360 g l^{-1})
Potassium ferricyanide	60 oz gal^{-1}	(360 g l^{-1})
Temperature	150 °F	(66 °C)

32.11 Glossary of trade names for coating processes

32.11.1 Wet processes

(1) PHOSPHATE PROCESSES

Processes by which a coating of phosphate is produced on the surface of steel or zinc base alloys by treatment in or with a solution of acid phosphates. For rustproofing, the metal must receive a finishing treatment with paint, varnish, lacquer or oil; examples of typical finishing treatments are given under *Parkerizing* but it should be understood that firms using or marketing other proprietary phosphate processes may apply different designations or use different media for the necessary finishing treatment.

Bonderizing A proprietary phosphate process applied to steel and zinc, marketed by Ardrox Pyrene Ltd. (similar to Parkerizing for steel but produces a thinner and less protective coating; synonymous with Parkerizing for zinc alloys).

Coslettizing The original phosphate process for steel, introduced in 1903.

Electro-granodizing A proprietary phosphate process applied to steel, marketed by ICI Ltd. (Paints Division). The chemical action of the solution is assisted by electrolysis.

Granodizing Proprietary phosphate processes applied to steel and zinc marketed by ICI Ltd. (Paints Division).

Lithoform A proprietary phosphate solution applied to zinc, marketed by ICI Ltd. (Paints Division).

Parkerizing A proprietary phosphate process applied to steel and zinc, marketed by Ardrox Pyrene Ltd. Examples of subsequent finishing treatments are:

P20	Dewatering black finish
P41	Black shellac finish
P75	Oiled finish
P96	Oiled finish
SP55	Mineral oil finish

Walterizing A proprietary phosphate process applied to steel and zinc base alloys, marketed by the Walterisation Co., Ltd.

(2) ALKALINE OXIDATION PROCESSES

Processes by which a black oxide film is formed on steel by treatment in a strongly alkaline solution containing an oxidizing agent. For rustproofing, the metal must receive a finishing treatment which is usually carried out with oil.

Black Magic Blackening processes marketed by M&T Chemicals Ltd.
Blakodizing Black chemical finishes on steel, marketed by Tool Treatments Ltd.
Ebonol Range of conversion coating processes for both ferrous and non-ferrous metals, marketed by OMI-Imasa (UK) Ltd.
Jetal An American process marketed by Technic Inc.

(3) CHROMATE PROCESSES

Alocrom Chromating solutions marketed by ICI Paints Ltd.
Enthox Chromating solutions marketed by OMI-Imasa (UK) Ltd.
Kenvert Chromating solutions marketed by the 3M Company Ltd.

(4) ANODIC OXIDATION OF ALUMINIUM AND ITS ALLOYS (ANODIZING)

For protection against corrosion and wear, for decoration, for aiding heat emission and for miscellaneous uses based on the absorptive properties of the oxide film when freshly made; used in conjunction with electrolytic 'polishing' for producing reflectors. Processes involving electrolytic treatment in solution, generally of chromic, sulphuric or oxalic acid with the production of a relatively thick film of oxide.

Anobrite Bright anodizing process operated by Anobrite Ltd.
Bengough–Stuart process (chromic acid) The first anodizing process patented in 1923.
Brytal process A process of producing reflectors introduced by British Alcan Aluminium.
Eloxal A generic term used in Germany for anodic oxidation.
Phosbrite process Chemical polish for bright anodizing marketed by Albright & Wilson Ltd.

(5) IMMERSION PROCESSES FOR THE TREATMENT OF ALUMINIUM ALLOYS

Alocrom process A process of priming a thin greenish yellow film in a cold acid solution containing chromates. Marketed by ICI Ltd. (Paints Division).
Alumon Zincating process marketed by Enthone/Imasa Ltd.
Bondal Zincating process marketed by W. Canning Ltd.
Decoral Oxidizing process giving electrically conducting coatings capable of being coloured by dyeing. Marketed by Lea Manufacturing Co. Ltd.
MBV process (Modified Bauer Vogel) A process of forming a thin oxide film by immersion in an alkaline solution containing chromates.
Pylumin process A similar process marketed by Ardrox Pyrene Ltd.

(6) NON-ELECTROLYTIC PROCESSES

Enplate Electroless nickel plating solutions, marketed by Enthone/Imasa Ltd.
Niklad Electroless nickel plating solutions, marketed by Lea Manufacturing Co. Ltd.
Sylek Electroless nickel–boron plating solutions, marketed by Imasa Ltd.
Transiflo Mechanical plating process, marketed by the 3M Company Ltd.

(7) ELECTROPLATING AND ELECTRODEPOSITION PROCESSES

Achrolyte Tin–cobalt alloy plating process marketed by Udylite/Oxy Metals Ltd.
Alecra 3000 Trivalent chromium plating process marketed by Albright and Wilson Ltd.
Brylanizing Zinc coating of wire by the 'Bethanizing' electroplating process of the Bethlehem Steel Co.
Chromonyx Black chromium plating process, often used for coating solar panels. Marketed by Harshaw Chemicals Ltd.
Fescolizing A term applied by Fescol Ltd., to any electrodeposition process carried out by them (incomplete without mention of the metal referred to, e.g. Fescolizing in chromium, etc.). Now carried out by British Metal Treatments Ltd.

Listard process–Van der Horst process Patented processes of hard chromium plating for protecting the cylinders of internal combustion and other engines from wear. These processes give an oil-retaining surface to the chromium. The processes are operated by British Metal Treatments Ltd.

Niron Bright nickel–iron plating process, marketed by OMI-Imasa (UK) Ltd.

Rovalizing A term applied by International Corrodeless Ltd., to any protective coating process used or marketed by them. Incomplete without description of the process referred to (e.g. Roval cadmium, etc., *see also* phosphate processes).

Tryposit A name used by Thomas Try Ltd., to indicate their special process of electrodepositing heavy nickel or hard chromium for engineering purposes.

Zartan Alloy deposit, used as an alternative to decorative chromium. Marketed by M&T Chemicals Ltd.

32.11.2 Dry processes

(1) THERMAL PROCESSES

The processes described below involve heating of the object to be coated in contact with the coating metal (in the form of powder or as a coating to secure inter-penetration) or with a compound of the coating element. Used for coating steel except where otherwise stated.

Aluminizing A process involving spraying with aluminium and heating to cause alloying.

Bower Barff A process of coating steel with a black oxide by heating in contact with steam.

Calorizing A process of coating with aluminium, similar to sherardizing (*see* below) but using aluminium in place of zinc.

Chromizing A process of coating with chromium involving heating to a high temperature in contact either with a vapour of chromous chloride or with metallic chromium.

Galvanizing A process of coating with zinc by dipping pickled steel into molten zinc (electrogalvanizing is sometimes used to mean electroplating with zinc).

Ihrigizing A process of coating with silicon by heating to a high temperature in contact with the vapour of silicon tetrachloride.

Nitriding A process of forming a hard layer on steel involving heating in a suitable atmosphere (usually ammonia vapour) to form a surface layer rich in nitride.

Sherardizing A process of coating with zinc involving heating in contact with zinc powder in revolving drums (introduced by Sherard Cowper Coles).

(2) METAL SPRAYING PROCESSES

A method of coating consisting of projecting a stream of molten metallic particles at high velocity against the surface to be coated. Mainly for protection against corrosion but also used for restoring the dimensions of undersized parts.

Wire or Schoop process A process marketed by Metallization Ltd., and Metallizing Equipment Co. Ltd., in which the coating metal in the form of wire is melted and atomized.

Schori or powder process A process marketed by Schori Metallizing Process Ltd., in which a stream of the powdered coating metal is fed into a flame and blown on to the surface to be coated.

Mellosing or molten metal process A process in which a molten metal is fed into a jet of heated compressed air which serves to atomize it and to project it against the surface to be coated.

Arc spray process A process in which the metal feed material is melted by an electric arc and then atomized by a stream of compressed air.

Plasma spray process A process in which a very high temperature plasma is produced by blowing gas through an electric arc. Metal wire or powder is melted by passage through the plasma and is projected by the gas on to the surface to be coated.

Detonation or D-gun process Oxygen, acetylene and the material to be plated, are introduced into a detonation chamber where a spark ignites the mixture. A detonation wave travelling at supersonic speed, forces the powdered material heated to $>3\,500°C$, on to the substrate. A special building is required for sound insulation. Very high density coatings of refractory materials like tungsten carbide, can be plated by the process.

33 Welding

33.1 Introduction

The 'Glossary of Welding Terms' is intended to explain the meaning of terms common in welding technology and used throughout this section and is not confined to British Standard terminology. For this, the reader is referred to BS 499.

Resistance welding, friction welding, diffusion bonding and fusion welding are considered separately, information on the welding of common materials being included in each section.

A list of British Standards relating to welding is given in Section 33.6.

33.2 Glossary of welding terms

Arc blow In arc welding, the deflection of the arc by magnetic forces induced by the welding current or residual magnetism in the workpiece.

Arc welding A fusion welding process wherein the source of heat is an electric arc.

Argon arc welding A fusion welding process wherein the source of heat is an electric arc struck between an argon shielded non-consumable tungsten electrode and the work. The filler wire, if required, is added separately.

Atomic hydrogen welding A fusion welding process wherein hydrogen is dissociated in an arc struck between two tungsten electrodes afterwards recombining to supply the welding heat. The filler wire is added separately.

Autogenous welding Fusion welding without a filler metal addition, in which the weld metal is provided by melting of the parent material.

Backward welding A fusion welding technique in which the source of heat is directed towards the already deposited weld.

Backing bar A bar of material used for backing up a joint during welding to control penetration at the root and not contiguous with the weld.

Backing strip A strip of metal used for backing up a joint during welding and which may or may not be left on after welding.

Backing run See *Sealing run.*

Backstep welding Welding in which increments of a run are deposited in a direction opposite to the general direction of welding.

Bead-on-plate weld A single run of weld metal deposited on an unbroken surface.

Braze welding A joining process whereby a brazing type of filler is deposited in a prepared joint using a *gas* welding technique.

Bronze welding A joining process whereby a brazing type of filler is deposited in a prepared joint using an *arc* welding technique.

Butt weld A weld between two members lying approximately in the same plane and not overlapping.

Carbon arc welding A fusion welding process wherein the source of heat is an arc struck between the work and a non-consumable carbon electrode. A filler wire may or may not be used. A shielding gas may also be employed.

Carbon dioxide welding A carbon dioxide shielded metal arc welding process using a continuous consumable bare wire electrode.

Chain intermittent fillet welding Two lines of intermittent fillet welding on either side of a joint wherein the fillet welds on one side are opposite those on the other side.

Cold welding Pressure welding at room temperature.

Constant potential power source A power source, the output voltage/ampere characteristic of which is substantially parallel to the current axis. Ideal for self-adjusting arc welding.

Controlled arc welding Metal arc welding in which the arc length is kept constant by controlling, from the arc voltage, the rate of feed of the consumable electrode.

Controlled tungsten arc welding Tungsten arc welding in which the arc length is controlled from the arc voltage.

Cored electrode (or cored wire) A consumable electrode in tubular form having a core of flux or other materials.

Corner weld An outside weld between two members approximately at right angles forming an L.

Cover glass A clear glass, sometimes gelatin coated, used in welders' helmets and hand shields to protect the filter glass from spatter and fumes.

Crater A depression left in the weld metal at the termination of a run.

Diffusion bonding A joining process wherein the component parts are held together under a pressure too low to cause significant plastic deformation, generally at an elevated temperature. The resultant atomic diffusion causes bonding, sometimes with the formation of a liquid phase.

Dip transfer A mode of particle transfer in gas-shielded metal arc welding wherein use is made of controlled short circuits between electrode and pool.

Downhand weld See *flat position weld.*

Drooping characteristic power source A power source, the output voltage of which falls as current demand increases. Necessary for manual metal arc welding and controlled-arc welding.

Edge weld A weld between the edges of two or more parallel and faying members.

Electrogas welding A vertical butt welding process using a gas-shielded consumable electrode to deposit metal into a molten pool held in place by moving dams which move upwards as the joint is made.

Electron beam welding A fusion welding process employing a high voltage focussed electron beam to supply energy.

Electroslag welding A vertical butt welding process in which the filler metal electrode is melted in a rising bath of conducting slag held in position by moving dams.

Explosive welding A pressure welding process employing the energy from the controlled explosion of sheet explosive to effect joining.

Face of weld The exposed surface of a fusion weld on the side from which welding was carried out.

Faying surface That surface of a member which is in contact with another member to which it is to be joined.

Filler wire Metal to be added in making a weld, usually in the form of a bare or flux-coated wire.

Fillet weld A weld of approximately triangular cross-section between two members approximately at right angles to each other.

Filter glass A dark coloured glass used to cut down the radiation from a fusion welding process to assist vision and protect the eyes of the welding operator. *See* BS 679.

Flash butt welding A resistance welding process wherein coalescence is produced by the heat obtained from resistance to the flow of a heavy electric current between two lightly abutting surfaces and by the application of pressure upon attainment of welding temperature.

Flat position weld A fusion weld in which the weld face is approximately horizontal and uppermost.

Forge welding A group of welding processes wherein coalescence is produced by applying pressure or blows to material rendered plastic by heating.

Forward welding A fusion welding technique in which the source of heat is directed ahead of the already deposited weld.

Friction welding A hot pressure welding process in which frictional heat is produced by rotating one component of the joint against a stationary mating surface under slight pressure. An upset force is applied when rotation is stopped. Orbital or oscillating movement may be employed rather than rotation.

Fusion boundary The boundary between weld metal and parent metal in a fusion weld.

Fusion welding All welding processes in which the weld is made by fusion of the parent metal by means of externally applied heat but without hammering or pressure. Filler wire may or may not be added.

Gap The minimum distance at any cross-section between edges, ends or surfaces to be joined.

Gas welding A fusion welding process in which the source of heat is the combustion of gas.

Hammer welding A forge welding process in which the welding pressure is obtained by means of hammer blows.

Heat affected zone The parent material alongside a weld which is heated during the welding operation.

High frequency induction welding A resistance welding process wherein coalescence is produced by the application of pressure to edges heated by the skin effect of high frequency alternating current.

High frequency injection The superimposing of a high frequency voltage on the alternating current used in argon-arc welding to ensure that the arc will restrike at the beginning of electrode positive half-cycles.

Horizontal vertical welding A weld made in such a position that the longitudinal axis of the weld is approximately horizontal and the plane of the weld face is approximately vertical.

Inert gas metal arc welding A group of fusion welding processes in which the source of heat is an electric arc struck between the work and an inert gas shielded, continuous, consumable electrode which acts as filler metal.

Interpass temperature In a multiple pass weld, the lowest temperature of the deposited weld metal before the next pass is started.

Lap weld A fillet weld between two overlapping members.

Laser welding A fusion welding process employing the energy from the excitation of an optical laser.

Leg of a fillet weld The distance from the root of the joint to the toe of a fillet weld.

MAG (metal active gas) welding Gas-shielded metal-arc welding with a consumable wire electrode, shrouded by active or non-inert gas.

Manual metal arc welding Metal arc welding using a flux-coated wire or rod electrode under manual control.

Metal arc welding An arc welding process in which the metal electrode forms the filler metal.

MIG (metal inert gas) welding See *Inert gas metal arc welding.*

Nugget The fusion zone of a spot, seam or projection weld.

Overhead position weld A weld made on a surface lying horizontally or at an angle not more than 45° to the horizontal, the weld being made from the underside of the parts joined. Alternatively a weld carried out on the underside of a joint.

Overlap Protrusion of weld metal beyond the bond at the toe of the weld.

Penetration The maximum depth a weld extends from its face into a joint, exclusive of reinforcement. In resistance welding, the distance from the interface to the edge of the weld nugget measured on a cross-section through the centre of the weld and normal to the surface.

Plasma arc An arc which is constricted mechanically or magnetically to produce a high heat concentration over a small area.

Plug weld A fusion weld made in a hole formed in one of the parts of a lapped joint to attach the other part.

Positional welding Welding carried out in all positions other than the normal flat position.

Pressure welding A process of joining metals in which the surfaces to be joined are brought into close contact by pressure either cold or heated below the melting point.

Projection welding A resistance welding process in which current and pressure concentration for making a weld is achieved by means of small projections usually raised on one of the workpieces.

Pulsed welding Arc welding, usually gas shielded, in which one or more welding variables, but most commonly current, are periodically varied between two levels.

Reinforcement Weld metal in a butt weld lying outside the plane joining the toes of the weld.

Resistance butt welding A resistance welding process in which the parts to be joined are butted together under pressure while current is allowed to flow until a predetermined temperature is attained and metal at the interface is upset and a weld produced.

Resistance welding A generic term covering those welding processes in which the welding heat is produced by the electrical resistance of the weldment and interfacial contact resistance during passage of the welding current.

Reverse polarity In direct current welding, the arrangement of current supply wherein the work is made the negative pole and the electrode the positive pole of the welding circuit. The term is misleading, and it is preferable to refer to polarity.

Roller spot welding A spot welding process using a machine similar to that used in seam welding. Pressure is applied continuously and current intermittently.

Root (a) The zone in the preparation for V, U, J and bevel butt welds, in the neighbourhood of and including the gap.

(b) The zone between the prepared edges adjacent to a backing strip in an open square butt weld.

(c) The zone, in parts to be fillet welded, in the neighbourhood of the actual or projected intersection of the fusion faces.

Root face That portion of the groove face adjacent to the root and normal to the face of the weld.

Root gap The separation between the members to be joined at the root of a joint.

Run-on and run-off tags Small pieces of metal tacked to a weldment at the beginning and end of welds to facilitate avoidance of undercutting at free edges and to remove the start and stop positions from the components being welded.

Sealing run A weld bead laid along the back of a groove weld.

Seam welding A resistance welding process in which a continuous weld is produced in overlapped sheets by means of two electrode wheels or between an electrode wheel and an electrode bar. The electrode wheels provide continuous pressure and current flow is intermittent with accurately timed periods.

Self-adjusting arc welding Metal arc welding in which the consumable electrode is fed into the arc at a constant speed with a high current density, any alteration in arc length being corrected by naturally occurring changes in the burn-off rate.

Series welding The making of two spot or seam welds or two or more projection welds simultaneously with electrodes forming a series circuit.

Size of weld (a) Butt weld—The joint penetration.
(b) Fillet weld—The leg length of the largest isosceles right-angled triangle which can be inscribed within the fillet weld cross-section.

Spot welding A resistance welding process in which overlapping parts are welded at one or more spots by means of shaped electrodes which give a high current density at the welding point and maintain mechanical pressure on the weld during and after current flow.

Spray transfer A transfer mode in gas-shielded metal arc welding, wherein metal transfers from the electrode to the weld pool as a stream of droplets.

Staggered intermittent fillet welding Two lines of intermittent fillet welding on either side of a joint wherein the fillet welds on one side are staggered relative to the fillet welds on the other side.

Stitch welding A spot welding process in which the welds overlap.

Straight polarity In direct current welding, the arrangement of current supply wherein the work is made the positive pole and the electrode the negative pole of the welding circuit. The term is misleading, and it is better to refer to actual polarity.

Stringer bead A weld bead deposited without appreciable transverse oscillation of the electrode.

Strip cladding A method of surfacing components by automatic submerged arc or gas-shielded arc welding, using a consumable electrode in the form of a strip rather than wire.

Submerged arc welding Arc welding in which a bare wire consumable electrode is used, the arc being enveloped in a powdered flux, some of which fuses to form a protective slag covering the weld.

Surge injection A means of arc re-ignition whereby a timed uni-directional medium voltage surge is applied across the arc gap. Used in a.c. argon-arc welding.

Synergic welding MIG or MAG welding system in which arc parameters are automatically set and controlled, normally for a specific wire feed speed.

Tack weld A short weld used in assembly of parts and for preventing distortion during welding.

Thermit welding A fusion welding process where the heat for fusion is obtained from liquid steel resulting from a thermit reaction, the steel so produced being used as the added metal.

Throat of a fillet weld (a) Theoretical. The distance from the beginning of the root of the joint perpendicular to the hypotenuse of the largest right-angled triangle that can be inscribed within the fillet weld cross-section.
(b) Actual. The shortest distance from the root of a fillet weld to its face.

TIG (tungsten inert gas) welding Arc welding using a non-consumable tungsten electrode, surrounded by an inert gas shield. (See *Argon arc welding.*)

Toe of weld The junction between the face of a weld and the parent metal.

Touch welding A metal arc welding technique employing flux coated electrodes of special type, whereby the tip of the rod is rested on the parent metal during welding.

Undercut A groove melted into the parent metal at the toe of a weld and left unfilled by weld metal.

Vertical position weld A weld made in such a position that the longitudinal axis of the weld is approximately vertical.

Weaving The deposition of a weld bead with transverse oscillation of the electrode.

Weldment An assembly whose component parts are joined by welding.

Weld metal That portion of metal which has been molten during welding.

33.3 Resistance welding

There are four main types of resistance welding process: spot welding, projection welding, resistance butt welding and flash butt welding. Seam, stitch and roller spot welding are closely related to spot welding.

Spot welding finds application in the lap joining of sheet material in the range of thickness from 2×0.3 mm to 2×4 mm and occasionally thicker materials. Stitch and seam welding are used for the manufacture of pressure-tight seams, stitch welding being more suitable for irregularly shaped components and seam welding for long, straight runs or curves with regular or generous radii. Multiple pressure and heating cycles are possible in stitch welding and roller spot welding, but not in seam welding. Roller spot welding is used for producing long, straight rows of spots at higher production rates than are possible in spot welding.

Projection welding may also be used for lap joining of sheets provided the material has sufficient ductility for the production of suitable projections and sufficient strength in the projections to withstand the high loads employed. This process is also used for the production of T-joints and the attachment of studs, nuts, collars and discs to sheet materials. Cross-wire welding is regarded as a form of projection welding.

Resistance butt welding is mainly used for the butt joining of wire and light gauge rods. Heating is more widespread, power consumption is higher and the condition of the end faces is more important than in *flash butt welding*. The latter process is used for butt joining of heavier and more complex sections and bevel joining.

33.3.1 The influence of metallurgical properties on resistance weldability

The properties of most importance which influence weldability, and therefore the selection of suitable welding conditions, are conductivity, expansion characteristics, nature and condition of the surface film, high temperature strength and the structure of the fusion and/or heat affected zone.

High conductivity materials require more current than mild steels to give an equivalent heat input for two reasons, first, due to the increased electrical conductivity and secondly, due to the increased conduction of heat away from the weld area. In practice, high conductivity materials such as aluminium are welded for short times with exceptionally high currents. There is, therefore, a need for more complex and expensive equipment for welding these materials than would be required for mild steel. Splashing or boiling of the weld metal may occur in low conductivity materials, and short times and high currents are used for such cases also.

Coefficient of thermal expansion and shrinkage contraction on solidification are important factors in governing the type of mechanical system used in welding machines. In materials of high thermal expansion and of high thermal conductivity, where shrinkage takes place relatively quickly, it is necessary to provide a high electrode force immediately following the current pulse, in order to avoid shrinkage cavities and cracks.

Consistency of surface condition is extremely important in most resistance welding processes (flash butt welding is an exception), particularly in materials with thick natural oxide films, such as aluminium and magnesium alloys. Cleaning procedures are invariable recommended in such cases. Thin and uniform oxide films, such as those obtained on pickled stainless steels and Nimonic alloys, give consistent welding behaviour, particularly with high electrode forces. Rust, paint and grease influence consistency, and should be removed. Metallic coatings do not commonly interfere with weldability seriously, although consistency may suffer slightly and electrode tip life in spot welding may be reduced.

Materials which have high strength when hot require high electrode forces in order to maintain a seal around the molten weld metal.

It is important that the metallurgical structure of both weld and heat affected zone should be adequate to withstand the demands made upon the joint in service. The heat affected zone in many alloys is softened, and it is therefore important to limit its extent by the use of short times. Ferritic steels suffer from hardening, which increases with carbon and alloy content. In serious cases this may necessitate some form of post-weld heat treatment to overcome the resulting brittleness.

33.3.2 The resistance welding of various metals and alloys

STEELS

Low carbon steels may be readily resistance welded by all processes, clean deep drawing steel being commonly regarded as excellent in this respect. A guide to the maximum carbon content

which can be tolerated in spot and projection welding without excessive hardening is given by the formula

$$C_{max} = 0.1 + 0.012t$$

where t = thickness in millimetres of the thinnest sheet in the combination.

Spot and projection welds in medium carbon and low alloy steels may be made, and it is desirable that a high electrode force be applied after the welding current pulse to prevent cracking followed by a tempering treatment which is most conveniently carried out in the welding machine. The electrode force may be maintained at a high level during tempering or reduced to its original value. Hardening is not such a serious problem in resistance butt or flash welding, since cooling rates are lower; however, butt welding is usually confined to steels that do not form refractory oxides.

Austenitic stainless steels require somewhat lower currents and higher electrode forces in spot and projection welding. In flash butt welding these materials require similar currents to mild steel, but with higher open-circuit voltages and upset forces.

Relative conditions for spot welding mild steel and other materials are summarized in Table 33.2.

Table 33.1 THE RESISTANCE WELDING OF METALS AND ALLOYS—SUITABILITY OF PROCESSES

	Process					*Process*			
Material	*Spot*	*Projection*	*Resistance butt*	*Flash butt*	*Material*	*Spot*	*Projection*	*Resistance butt*	*Flash butt*
Low carbon steel	S	S	S	S	Aluminium bronze	P	P	P	P
Low alloy steel / Medium carbon steel	P	P	S	S	Silicon bronze	S	—	S	-
					Cupronickel	S	—	S	-
Austenitic stainless steel	S	S	N	S	Nickel–silver	S	—	S	—
					Magnesium alloys	P	N	N	S
Aluminium and low-strength alloys	P	N	S	S	Nickel and its alloys	S	S	N	S
					Titanium	S	P	N	S
Medium and high-strength aluminium alloys	S	N	P	S	Zirconium	S	S	N	S
					Tantalum	S	—	—	—
Copper	N	N	S	S	Niobium	S	-	-	—
Beryllium-copper	S	—	S	S	Molybdenum	P	--	N	S
Gilding metals	N	N	S	N	Tungsten	P	—	N	S
70/30 and 60/40 brass	S	—	S	N					
Tin bronze	S	S	S	S					

S = Suitable. N = Not recommended. P = Possible under certain conditions.
— = Information not available.

Table 33.2 RELATIVE CONDITIONS FOR SPOT WELDING MILD STEEL AND OTHER MATERIALS

Material	*Electrode force*	*Weld time*	*Welding current*	*Remarks*
Mild steel	A-70 MPa on tip area	Short B	High C	
Low alloy steels	A × 1	B × 1	C × 1	Post-heating needed
18.8 stainless steels	A × 3	B × 1	C × 0.9	Surface oxides may cause trouble in rare cases
Nimonic alloys	A × 4	B × 1	C × 0.9	
Nickel	A × 2.5	B × 1	C × 1.5	
Monel, Inconel	A × 4	B × 1	C × 0.9	
Aluminium alloys	A × 2	B × 0.5	C × 4	Surface oxide must be removed
Cupronickel, silicon bronze, 70/30 brass, nickel-silver, etc.	A × 0.8	B × 0.8	C × 1.2 – 2.0	Current depends on conductivity of alloy
Titanium and its alloys	A × 2	B × 1	C × 1	Avoid excessive penetration

Taken from 'Resistance Welding', published by the former British Welding Research Association.

ALUMINIUM AND ALUMINIUM ALLOYS

The resistance weldability of aluminium alloys is governed mainly by their relatively high conductivity and the presence of a tenacious high resistance oxide film. Care is therefore required in surface preparation to produce a consistent contact resistance, and this is normally done by controlled scratch brushing or chemical dipping. The use of paste fluxes is not recommended, due to inconsistent quality. Degreasing alone is occasionally practised in applications where consistency is less important. Cleaning of outer surfaces improves tip life in spot welding.

The need for high currents and short weld times has already been mentioned, and comparative figures are given in Table 33.2.

In this group, pure aluminium is the most difficult material to spot weld, and probably the easiest to resistance butt weld. Strong aluminium alloys clad with pure aluminium do not give the same trouble in spot welding due to their lower conductivity and higher resistance to indentation Generally, spot welding difficulties increase with decreasing parent metal strength and increasing conductivity. All the common sheet materials may be spot welded.

There is little experience with projection welding, the main difficulty being the relatively low strength in compression of the projection. Resistance butt welding is used only for pure aluminium and low strength alloys in small sections, and care with surface preparation is again necessary. Flash butt welding can be used for most aluminium alloys, provided rapid heating and careful control in the time and speed of application of the upset force is applied.

COPPER AND COPPER ALLOYS

Due to its high conductivity, copper is not normally regarded as weldable by the spot and projection welding processes, although very thin copper may be spot welded with molybdenum tipped electrodes using very high currents and short times. The alternative of interposing of shim of relatively high resistance brazing filler metal is often employed, giving a resistance brazed joint rather than a weld. Pure copper may be satisfactorily resistance butt and flash butt welded, and both processes are used in the wire industry.

Cadmium–copper is difficult to resistance weld, and resistance brazing is preferred, but beryllium–copper may be readily spot or butt welded, provided the normal precautions for high conductivity materials are taken.

Brasses increase in weldability with increasing zinc content, and it is difficult to spot weld gilding metals, though 70/30 and particularly 60/40 brass may be welded satisfactorily by this process. Resistance butt welding is frequently used for brass wire, but flash butt welding is not suitable, due to zinc volatilization. Information on current, weld time and upset force compared with mild steel is given in Table 33.2. Certain brasses should be rendered immune from season cracking by a low temperature annealing treatment after welding.

Tin bronzes have relatively low conductivity, and may be readily joined by practically all resistance welding methods. Phosphor bronzes may, however, tend to stick to copper alloy electrodes in spot welding, and plating of the electrodes may be required.

Information on aluminium bronze is meagre, but satisfactory resistance welds of all types have been produced in single phase alloys. Flash butt welding has been used for complex alloys.

Silicon bronzes have low conductivity, and may be satisfactorily spot and resistance butt welded. Weld times and electrode forces are rather lower than for mild steel and currents somewhat higher. It is important that rapid follow up of the electrodes during heating should take place.

Cupronickels and nickel–silvers behave in a similar manner to silicon bronze.

MAGNESIUM AND MAGNESIUM ALLOYS

Magnesium and its alloys may be satisfactorily spot welded for low duty service using equipment similar to that used for aluminium alloys. Reference has been made to the satisfactory weldability of Mg-Mn, Mg-Al-Zn, Mg-Zn-Zr and Mg-Th-Zr alloys. Cleaning is important, chemical methods being preferred to mechanical methods, although good results can be obtained by brushing with wire wool. Electrode cleanliness is important if copper contamination of the work-piece is to be avoided. High currents and short weld times are used together with a rapid follow up of the electrodes to give a force somewhat lower than that used for aluminium. Radiused tip electrodes help to form a pressure seal around the weld.

Flash butt welding may also be used for magnesium alloys.

NICKEL AND NICKEL ALLOYS

Nickel, Monel,* Inconel* and the Nimonic* alloys may be satisfactorily spot, projection and flash butt welded.

Conditions for spot welding Nimonic alloys are similar to those for austenitic stainless steel but with somewhat higher electrode forces. Nickel requires higher currents and lower forces although forces are still much higher than for mild steel. Monel and Inconel require currents and forces similar to those recommended for Nimonic alloys. Comparative figures are given in Table 33.2. Cleanliness is important, sulphur and lead contamination being particularly dangerous. Sticking which may occur when spot welding annealed nickel, may be overcome by silver plating of the electrodes. Cracking may be encountered with some precipitation hardening alloys if electrode pressure is too low. Increased weld time and pressure are beneficial.

Flash butt welding is satisfactory if clamping is firm to prevent arcing, clamping distances are kept short because of the low conductivity and upset forces are high. Open-circuit voltages require to be higher than used for mild steel.

REFRACTORY METALS

Among this group of materials are included titanium, zirconium, tantalum, niobium, molybdenum and tungsten. The problem of contamination by reaction with the atmosphere is not as serious in spot welding as in fusion welding, but the quality of projection welds may be improved by the use of an inert atmosphere.

Titanium may be readily spot or flash butt welded. Conditions for spot welding are similar to mild steel but with higher electrode forces. The high electrical resistance tends to give a large weld with high penetration, and seam welding may need to be done under water to prevent contamination after welding. Flash welding conditions are similar to those used for aluminium alloys. Projection welds have also been made in titanium.

Zirconium in thin gauges may be spot welded using conditions similar to those used for stainless steel. No special cleaning other than degreasing is normally necessary. Projection welding and flash butt welding are also possible.

Tantalum may be spot welded in thin gauges, and welding may be carried out in air if the time is less than one cycle. Larger times require water cooling of the weld area. Surfaces should be degreased and pickled in a sulphuric/chromic acid mixture. Niobium should be treated in a similar way.

Resistance welds in molybdenum and tungsten are often inherently brittle due to the high brittle/ductile transition temperature of the recrystallised and as cast materials. Other problems are contamination of surfaces with electrode materials and contamination of the electrodes themselves. These troubles are minimized by welding under water. Surfaces should be thoroughly cleaned, if possible by grit blasting. Both materials may be resistance brazed readily, using shims of tantalum, zirconium or nickel. Both materials have been satisfactorily flash butt welded.

DISSIMILAR METALS

It is normally easier to make satisfactory joints between dissimilar metals by resistance welding or resistance brazing than by fusion welding or normal brazing techniques, since the problem of fluxing does not arise and techniques may be chosen to minimize the danger of brittle intermetallic phases within the joint. Copper and aluminium, for example, form a series of brittle phases when melted together, but flash butt welding of copper to aluminium is widely practised, since these phases are forced out of the joint when the upset force is applied.

When spot welding dissimilar metals, it may be necessary to use electrodes of differing conductivity against the different parts, i.e. a high conductivity electrode against the lower conductivity material.

Some indication of the spot welding characteristics of dissimilar metals is given in Table 33.3. In some cases where spot welding is not possible due to excessive formation of intermetallics, it is possible to interpose a layer of a third material compatible with both the parts requiring to be joined.

* Henry Wiggin & Co. Ltd.

Table 33.3 SPOT WELDING OF DISSIMILAR METALS

		Nimonic	*Monel, Inconel*	*Nickel*	*Phosphor bronze*	*Silicon bronze*	*Nickel–silver*	*25–40% zinc brass*	*10–25% zinc brass*	*Copper*	*Aluminium and alloys*	*18/8 stainless steel*	*Mild steel*			
													Other coatings	*Tin or zinc coated*	*Scaly*	*Clean*
Mild steel	Clean	G 5 7	P 8	P 8	P 8	P 8	P 8	P 6 8	U 6 8	U 6 8	P 6 8	G 5	P 3 4	G 3 4	P 2	E 1
	Scaly				U 2 8	U 2 8	U 2 8				U 2 8 6	U 2	U 2 4 3	U 2 4 3	P 2	
	Tin or zinc coated		P 3 8 4	P 3 4	P 3 4	P 3 4	P 3 4	P 3 6 4	U	U	U	G 3 4	P 3 4	G 3 4		
	Other coatings		U 3 8 4	U 3 4	U	U	U	U	U	U	U	U	P 3 4			
18/8 stainless steel		G 5	P	P	P	P	P	U	U	U	U	E 5				
Aluminium and alloys		U	U	U	P 5 7	P 5 7		P 5 7	U	U	G 5 7					
Copper		U	U	U	P 6 8 7	P 6 8 7	P 6 8 7	P 6 8 7	U	U						
10–25% zinc brass		U	U	U	U	U	U	U	P							
25–40% zinc brass			P 5 7	P 5 7	P 5 7	P 5 7	P 5 7	G 5 7								
Nickel–silver			G	G	P	P	G									
Silicon bronze			P	P	P	G										
Phosphor bronze			P	P	G											
Nickel			G	G												
Monel, Inconel			G													
Nimonic		G 5 7														

Key: Spot weldability: E Excellent; G Good; P Poor; U Unsatisfactory.
Taken from 'Resistance Welding', published by the former British Welding Research Association.

Notes:

(1) Wide range of welding conditions.
(2) Inconsistent welds of poor strength. Shot blasting or pickling recommended.
(3) Coating thickness should be uniform.
(4) Electrodes should be cleaned frequently to prevent sticking.
(5) High currents and short times preferred.
(6) Thin gauges may be welded with special conditions.
(7) Welding conditions must be accurately controlled.
(8) Low weld strength.

33.4 Friction welding

The most common method of generating frictional heat for welding is to rotate one component relative to the other under an axial load. When the metal temperature at the interface is sufficiently high, the rotation is stopped, and the workpieces are forced together under the original or higher load. Inertia welding is a variant of the process, using the kinetic energy of a flywheel to provide rotation and thermal energy. In friction welding, one component usually has a circular cross-section, but this is not always essential, particularly when orbital rather than rotational differential movement of the workpieces is used.

In radial friction welding, two lengths of tube are aligned axially with a small gap, and a collar of tapered cross-section is rotated between them to generate heat at both interfaces simultaneously. The tubes do not rotate but are forced together during the forging stage of the operation. For linear friction welding, the parts to be joined are oscillated along one axis parallel to the faying surfaces, and are aligned as required immediately prior to forging.

The principal welding variables are the welding speed, applied heating pressure, forge pressure, and heating duration. For any particular joint configuration, selection of optimum welding conditions is primarily dependent on material strength and thermal conductivity characteristics, although with dissimilar metal joints, it may be necessary to use conditions minimising the formation of brittle phases at the interface.

Welding speed is not generally critical, peripheral velocities of between 0.3 and 7 m s^{-1} being common for a range of materials. Higher welding speeds increase the width of the heat-affected zone (HAZ) and welding time.

Both heating and forge pressures must be selected to achieve uniform heating and maintain the faying surfaces in intimate contact. Typical values for mild steel are 45 MPa and 75 MPa for heating and forging, respectively. With mild steel, doubling the heating pressure increases the power required by 50%. Excessive pressure is to be avoided with alloy steels, since the steep temperature gradient may lead to the formation of hard structures, with reduced ductility. Higher pressures are required for materials of greater hot strength. The heating pressure is particularly important in determining both the torque required to make the weld, and the temperature gradient at the interface. With high conductivity materials, such as copper, it is advantageous to use a low heating pressure to obtain rapid local heating, followed by a high forge pressure. Duration of heating is selected to obtain suitable thermal conditions for the production of a sound joint on forging, without overheating of surrounding material. For mild steel, times of 0.5–5 s are general depending on the joint geometry, lower times being applicable to smaller sections, or higher conductivity materials.

Since it is to some extent self-cleaning, the method is tolerant with respect to surface preparation. The atmosphere is excluded from the weld area, and reactive metals can be joined with no special precautions, while the absence of a liquid phase during welding may avoid problems of porosity, cracking, etc., associated with fusion processes. In fact, if a low melting point liquid area is formed at the interface, it may act as a lubricant, and restrict the development of frictional heat essential for welding. This can arise when welding on to galvanized steel, unless the zinc is removed from the abutting region. Sulphur-bearing free machining steels cause similar difficulties.

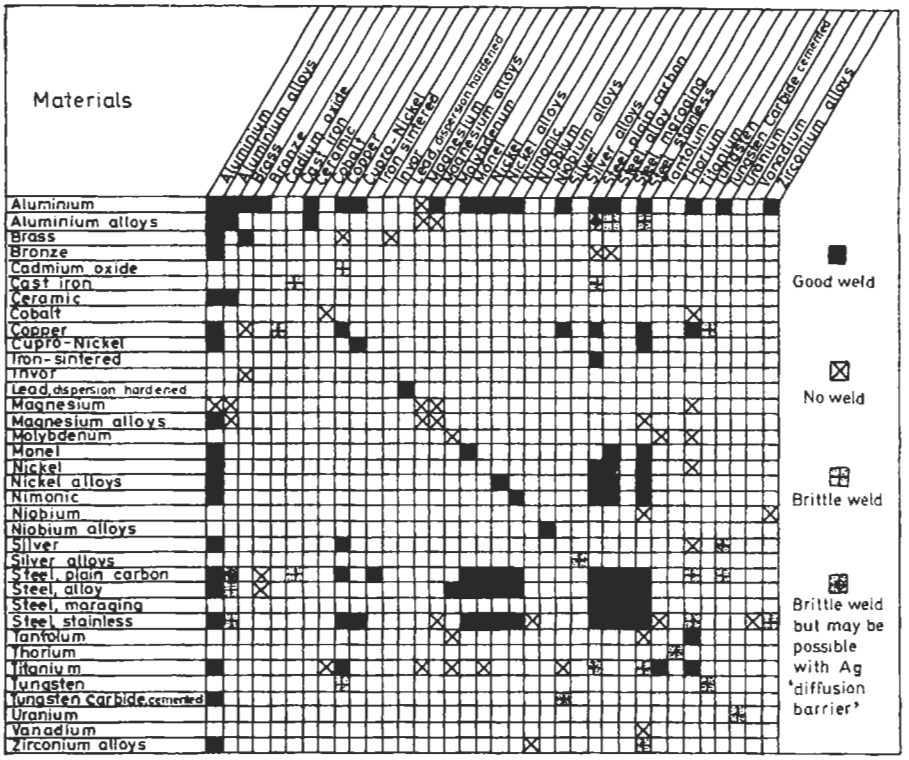
Most common alloys are weldable to themselves, while a number of dissimilar metal combinations can be joined, that are normally weldable by other techniques. Table 33.4 illustrates the relative weldability of a range of materials.

DIFFUSION BONDING

In diffusion bonding, contacting surfaces are joined by the simultaneous application of temperature and pressure, using conditions adequate for diffusional processes to occur, but insufficient for macroscopic deformation. As most commonly practised, it is a solid-state process, but a liquid phase may be present stemming either from interdiffusion of dissimilar metals, or from the incorporation of an interlayer into the joint. Interlayers can be applied by vacuum spraying, galvanizing or as powder or foils, and are employed to accelerate diffusion or to prevent the formation of brittle intermetallic phases. Bonding is normally carried out in vacuum, although protective gas shielding can be used. The range of metals and alloys which have been bonded either directly or indirectly via an interlayer is illustrated by Table 33.5, with butt joint properties in Table 33.6. Bonds between metallic and non-metallic components such as glass or ceramics have been made.

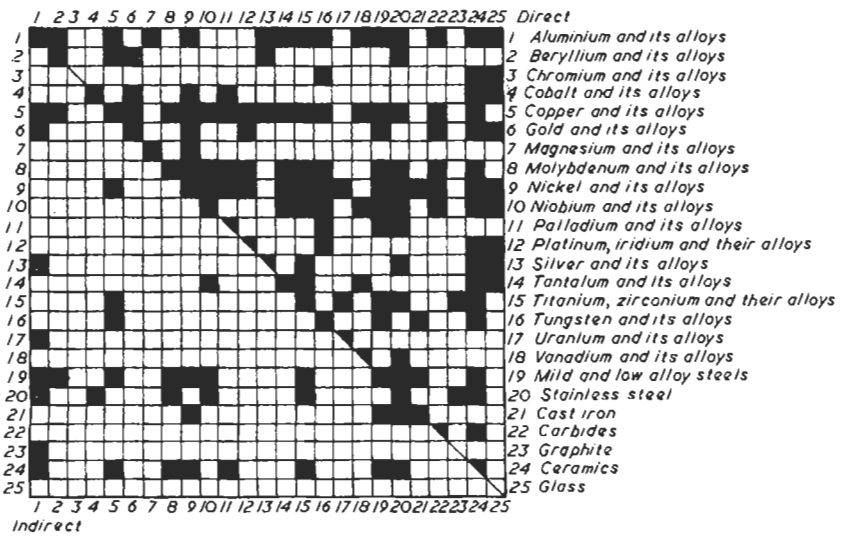
The process is governed by four main interrelated variables: pressure, temperature, time and surface condition. A summary of reported bonding conditions is given in Table 33.7.

Table 33.4 WELDABILITY OF DIFFERENT MATERIALS BY FRICTION WELDING*



*For further information, *see* C. R. G. Ellis, *Met. Const. & Brit. Weld. J.*, 1970, **2**, 185–188.

Table 33.5 DIFFUSION BONDED COMBINATIONS OF METALS AND ALLOYS WITHOUT AN INTERLAYER (DIRECT) AND WITH AN INTERLAYER (INDIRECT)*



*For further information, *see* P. M. Bartle, *Welding J.*, 1975, **54**, 799–804.

Table 33.6 EXAMPLES OF DIFFUSION BUTT JOINT PROPERTIES*

Material combination	*Joint strength*			*Tensile joint efficiency,%*
	tonf in^{-2}	ksi	MPa	
Mild steel/mild steel	30	66	465	100
High strength steel/high strength steel	75	165	1160	90
Mild steel/cast iron	28	61	430	100
Stainless steel/cast iron	34	75	525	100
Cast iron/cast iron	56	124	865	100
Mild steel/aluminium alloy	10	22	155	50
Aluminium alloy/aluminium alloy	10	22	155	50
Aluminium alloy/copper	9	20	140	70
Copper/nickel	14	31	215	100
Copper/copper	14	31	215	100
Nimonic/Nimonic	59	130	910	90
Stellite/Stellite	60	132	925	90
Titanium alloy/titanium alloy	69	152	1065	100

* For further information, *see* Table 33.5.

Table 33.7 DIFFUSION BONDING PARAMETERS*

Material I	*Material II*	*Interlay*	*t*, °C	*P*, MPa	*t*, min
Copper	Molybdenum	—	900	7.4	10
Copper	Steel	—	900	4.9	10
Copper	Nickel	—	900	14.7	20
Copper	Copper	—	800–850	5–7	15–20
Titanium	Nickel	—	800	9.8	10
Titanium	Copper	Molybdenum	950	4.9	30
Titanium	Copper	Niobium	950	4.9	30
Titanium	Copper	—	800	4.9	30
Molybdenum	Steel	—	1200	4.9	10
Tantalum	Tantalum	Zirconium	870	—	—
Niobium	Niobium	Zirconium	870	—	—
Zircaloy-2	Zircaloy-2	Copper	1040	20.6	30–120
Kovar	Kovar	—	1000–1110	20–25	20–25
Steel	Cast iron	Nickel	850–950	14.7	5.7
Steel	Aluminium	—	500	7.4	30
Steel	Aluminium	Silver	550	4.9	10
Steel	Steel	—	900–1100	5–15	10–60
Titanium	Titanium	—	850–920	3–10	10–60
Al alloys	Al alloys	Silver or copper	550	1–2	15

* For further information *see* P. Wiesner, *Met. Con. & Brit. Weld. J.*, 1971, **3**, 91–93.

PRESSURE

It is necessary to obtain intimate contact between the faying surfaces, and hence the pressure must be high enough to cause plastic deformation at the tips of abutting surface asperities and to induce creep so that contact over the entire surface area can be achieved. This implies pressures below, but often close to, the material yield stress at temperature and hence solid-state bonding pressures for a range of metals and alloys are typically 5–15 MPa, although higher pressures are required for refractory metals. With liquid phase diffusion bonding, pressures of 0.5–1.5 MPa are normal.

TEMPERATURE

To achieve sufficiently rapid creep for practical purposes, a minimum temperature of 0.7 T_m is normal, T_m being the material melting point in degrees kelvin. Higher temperatures may be used to accelerate bonding.

TIME

The diffusion time is strongly dependent on the temperature. Bonding can occur after only a few minutes, but times of 0.5–2.0 hours are preferred to give complete interface void removal by diffusion, and improved joint ductility.

SURFACE PREPARATION

The rate of bonding depends on the flatness and roughness of the faying surfaces, and a finish of ~0.4 μm is preferred. Removal of thick oxide layers and degreasing prior to bonding are required. although to some extent contaminants and oxides can dissolve in the parent material, especially with iron- and copper-base systems.

33.5 Fusion welding

While gas welding using an oxy-acetylene torch is still frequently used for mild steel and some non-ferrous metals in sheet gauges, arc welding processes account for the greater proportion of welding carried out at the present time.

Metal arc welding using a coated electrode is the most popular for the manual welding of mild and alloy steels, and electrodes are available for welding cast iron, nickel and its alloys, certain copper alloys and a limited range of aluminium alloys.

A greater number of processes are available for the mechanized welding of mild steel plates. The submerged arc process employs a bare wire electrode and a flux cover continuously supplied via a hopper ahead of the arc. In alternative processes, the flux is applied as a wrapping on the continuously fed electrode or in the core of an electrode formed from folded strip. Other processes using both flux and shielding gas (carbon dioxide) have been developed for mechanized fillet welding.

The gas-shielded processes may be applied to almost all metallurgical materials. They fall into two principal groups, namely those employing a non-consumable electrode, and those wherein the electrode is in the form of a continuous consumable wire.

The argon arc, or TIG, process is the best known of the former type and has been successfully employed for practically all the materials mentioned below, with the possible exception of cast iron. A.c. argon arc welding is normally recommended for aluminium and magnesium alloys and materials forming refractory films, such as aluminium bronze and beryllium copper, while d.c. electrode negative is used for steels, copper and nickel alloys. D.c. nitrogen arc welding is used for copper, and d.c. helium arc welding may be used in circumstances where the high gas cost can be justified in terms of higher welding speeds or increased penetration.

The gas-shielded metal arc processes have been applied to almost as wide a range of materials as the TIG process. The shielding gases used vary with the metals being welded, argon being used for aluminium, magnesium, nickel alloys and refractory metals, argon or nitrogen for pure copper, argon for copper alloys, and argon, argon–oxygen mixtures or carbon dioxide for all types of steel, including stainless steels. D.c. electrode positive is invariably used in present commercial equipment. CO_2 welding is particularly valuable as a low hydrogen process for welding low alloy steels.

Atomic hydrogen and carbon–arc welding are only occasionally used, mainly for mild steel sheet metal welding.

Fusion welding can also be achieved by the electron beam and laser processes. Both processes are applicable to a range of ferrous and non-ferrous alloys, and because of the high energy density, they give a rapid thermal cycle and little distortion. The former method is normally (although not solely) carried out in vacuum and hence is especially appropriate for reactive metals. Laser welding commonly employs helium shielding, this gas having a high ionization potential with reduced energy loss from the laser beam and, for the same reason, helium is also used for out-of-vacuum electron welding.

33.5.1 The fusion welding of metals and alloys—ferrous metals

MILD STEELS

The welding of mild steel may be accomplished by the majority of processes, the choice of method being dependent upon thickness, type and position of joint and to some extent the type of steel

employed. The processes most applicable to thin sheet are gas welding, TIG welding, CO_2 shielded metal arc welding, and less commonly, atomic hydrogen welding. The TIG and atomic hydrogen processes may be manual or mechanized.

Joints in thicker sheet and plate will generally employ the manual metal arc, or, if circumstances permit, one of the mechanized processes such as submerged arc or CO_2 welding. Cored wire welding, employing a continuous tubular consumable with a flux or metal powder core, also finds application. Plate of around 100 mm thickness and above may be welded in a single pass using the electroslag process.

The composition of the steel to be welded may limit the choice of process. Rimming steels can give porous welds in gas-shielded welding, and if a mechanized welding process is required, atomic hydrogen, providing a reducing atmosphere, would seem to be the most suitable. Killed steels give better results with argon arc and gas-shielded metal arc welding. High sulphur-free cutting steels are not recommended for welding, since the sulphur gives rise to hot cracking. If such steel has to be welded, basic coated metal arc electrodes should be used.

Gas welding

A neutral flame and no flux is used. The filler material is preferably copper coated to ensure freedom from rust. For general purposes, filler metal to BS 1453: 1972 A1 should be used. This is a low carbon mild steel giving a tensile strength of 330 MPa minimum. For somewhat higher strength A2 filler, containing manganese and silicon, is available; *see* Table 33.8.

Table 33.8 FILLER RODS FOR THE GAS WELDING OF FERRITIC STEELS (BS 1453:1972)

Type	*Element* wt %						*Typical application*
	C	Si	Mn	Ni	Cr	Mo	
A1	0.10 max	—	0.60 max	0.25 max	—	—	General purpose mild steel
A2	0.10–0.20	0.10–0.35	1.00–1.60	—	—	—	Mild steel, 420 MPa
A3	0.25–0.30	0.30–0.50	1.30–1.60	0.25 max*	0.25 max*	—	Medium tensile, 480 MPa
A4	0.25–0.35	0.10–0.35	0.35–0.75	2.75–3.25	-0.30	—	Heat treatable deposit
A5	0.35–0.45	0.40–0.70	0.90–1.10	—	0.90–1.20	—	Wearing surfaces
A6	0.15 max	0.25–0.50	0.60–1.50	0.20 max*	0.20 max*	0.45–0.65	Welding $\frac{1}{2}$% Mo steels
A7	0.08–0.15	0.10–0.35	0.80–1.10	—	—	—	Similar to A2 but lower alloy
A32	0.12 max	0.20–0.90	0.40–1.60	—	1.10–1.50	0.45–0.65	Welding 1$\frac{1}{4}$% Cr/$\frac{1}{2}$% Mo steels
A33	0.12 max	0.20–0.90	0.40–1.60	—	2.00–2.70	0.90–1.10	Welding 2$\frac{1}{2}$% Cr/1% Mo steels

* If present as a residual element.
Both S and P to be 0.040% max, for A1 to A7, and 0.030% max for A32 and A33.

Metal arc welding

The choice of electrode depends upon the application and the type of welding power source available. All electrodes supplied to BS 639:1986 are coded according to the following system:

1. *Compulsory part:*
 (a) The letter E for a covered manual metal-arc electrode.
 (b) Tensile and yield strength of deposited weld metal.
 (c) Elongation and Charpy impact values of deposited weld metal.
 (d) Type of flux coating.
2. *Optional part:*
 (e) Nominal electrode efficiency.
 (f) Welding positions in which the electrode can be used.
 (g) Recommended current and voltage conditions.
 (h) Whether or not the electrode is hydrogen controlled.

For full details of this system, BS 639:1986 should be consulted. The salient coating characteristics are summarized in Table 33.9.

Table 33.9 TYPES OF COATINGS FOR CARBON AND CARBON MANGANESE STEEL ELECTRODES IN BS 639:1986

Coding	*Type of covering*	*Resultant slag*	*Special features*
B	Basic lime-fluoxpar	Dense	Low weld metal hydrogen contents are possible, with high resistance to solidification cracking. Generally suitable for all welding positions
BB	Basic lime-fluospar with metallic material	Dense	As B, but higher deposition efficiency. Not normally suitable for vertical or overhead welding
C	Cellulosic	Thin and friable	High fusion rate and penetration. Can normally be used in all welding positions. High hydrogen level
R	Rutile	Fluid	Smooth arc with little spatter, and usable in all welding positions
RR	Rutile	Fluid, but more viscous than R	Similar to R, but with heavier coating thickness. Good weld surface finish
S	Various	Various	Includes acid or oxide fluxes. Consult manufacturer

Automatic processes employing flux

As with manual metal arc welding, the flux type involved is of considerable importance in the submerged arc process and in techniques employing flux-cored consumables. The choice of flux obtainable with these processes is more limited than is the case with manual metal arc welding but both rutile and basic fluxes (equivalent to Classes R and B in Table 33.9) are available for particular applications, together with more neutral fluxes.

Submerged arc welding fluxes may be in a fused or agglomerated form, depending on the method of manufacture, and have in the past normally been of a neutral or acidic character with high silicate content. More basic fluxes have been developed, which may offer advantages in the mechanical properties of deposited weld metal, but usually with more difficult slag detachment and a more irregular weld surface. Although not giving a full description of reactivity, fluxes are commonly categorized in terms of the 'basicity index' (BI), wt% of constituents:

$$\mathrm{BI} = \frac{\mathrm{CaO} + \mathrm{CaF_2} + \mathrm{MgO} + \frac{1}{2}(\mathrm{MnO} + \mathrm{FeO})}{\mathrm{SiO_2} + \frac{1}{2}(\mathrm{Al_2O_3} + \mathrm{TiO_2} + \mathrm{ZrO_2})}$$

Values of BI range from about 0.7 for an acid flux to 3.5 for a basic system. For details of BI see S. S. Tuliani *et al*, *Welding Metal Fabrication*, August 1969, 327–339.

Low carbon wire consumables are used, generally with added manganese and silicon as deoxidants.

Gas-shielded welding processes

Consumables used for gas-shielded welding of steels contain added deoxidants (usually silicon and manganese). Examples for mild steel are given in Table 33.10, A15 and A17. TIG welding is usually carried out using argon shielding for optimum weld pool control, although helium may be used on thicker sections to increase penetration of the weld. With gas-shielded metal arc welding of mild steel, the surrounding gas is generally CO_2 or argon/CO_2 mixtures.

LOW ALLOY STEELS

In general, the application of the various welding processes is similar for both mild and low alloy steels, the principal difference being that the choice of consumables for low alloy steels may be more limited. Manual metal arc and submerged arc welding are most widely used for low alloy steels in industry, consumables for the former process being given in Table 33.11.

It must be appreciated that in the heat-affected zone (HAZ) around a weld, very high cooling rates may be experienced. Particularly with alloy steels, hard HAZ microstructures can be produced, having a high susceptibility to cracking under the influence of residual welding stresses, and hydrogen picked up during the welding operation. The necessity to avoid hydrogen induced cracking is a major factor in the selection of welding conditions for low alloy steels.

Table 33.10 FILLER RODS AND WIRES FOR GAS-SHIELDED ARC WELDING OF FERRITIC STEELS (BS 2901:PART 1:1983)

	Element wt %							
Type	C	Si	Mn	Cr	Mo	Al	S	P
A15*	0.12 max	0.30–0.90	0.90–1.60	—	—	0.04–0.40	0.040 max	0.040 max
A16	0.25–0.30	0.30–0.50	1.30–1.60	—	—	—	0.040 max	0.040 max
A17	0.12 max	0.20–0.50	0.85–1.40	—	—	—	0.040 max	0.040 max
A18	0.12 max	0.70–1.20	0.90–1.60	—	—	—	0.040 max	0.040 max
A19	0.08–0.12	0.30–0.50	1.00–1.30	—	—	0.35–0.75	0.040 max	0.040 max
A30	0.12 max	0.02–0.90	0.40–1.60	—	0.45–0.65	—	0.030 max	0.030 max
A31	0.14 max	0.50–0.90	1.60–2.10	—	0.40–0.60	—	0.030 max	0.030 max
A32	0.12 max	0.20–0.90	0.40–1.60	1.10–1.50	0.45–0.65	—	0.030 max	0.030 max
A33	0.12 max	0.20–0.90	0.40–1.60	2.00–2.70	0.90–1.10	—	0.030 max	0.030 max
A34	0.12 max	0.20–0.90	0.40–1.60	5.00–6.00	0.45–0.65	—	0.030 max	0.030 max
A35†	0.10 max	0.50 max	0.60 max	8.00–10.50	0.8 –1.2	—	0.030 max	0.040 max

* Titanium or zirconium may be present up to 0.15% max each. † 0.5% nickel maximum.

Note: All grades have 0.4% copper maximum.

Table 33.11 MANUAL METAL ARC ELECTRODES FOR LOW ALLOY STEELS (BS 2493:1985)

	Element wt %							
Composition code	C	Si	Mn	Ni	Cr	Mo	S	P
Mo-steel								
MoB*	0.10 max	0.60 max	0.75–1.20	—	—	0.40–0.70	0.030 max	0.035 max
MoC, MoR	0.10 max	0.80 max	0.35 min	—	—	0.40–0.70	0.030 max	0.035 max
Cr–Mo steel								
1CrMoLB*	0.05 max	0.50 max	0.50–1.20	—	1.0–1.8	0.40–0.70	0.025 max	0.025 max
1CrMoB*	0.10 max	0.50 max	0.75–1.20	—	1.0–1.5	0.40–0.70	0.030 max	0.035 max
1CrMoR	0.10 max	0.30 max	0.35 min	—	1.0–1.5	0.40–0.70	0.030 max	0.035 max
2CrMoLB*	0.05 max	0.50 max	0.50–1.20	—	2.0–2.5	0.90–1.20	0.025 max	0.025 max
2CrMoB*	0.10 max	0.50 max	0.75–1.20	—	2.0–2.5	0.90–1.20	0.030 max	0.035 max
2CrMoR	0.10 max	0.30 max	0.35 min	—	2.0–2.5	0.90–1.20	0.030 max	0.035 max
5CrMoB	0.10 max	0.50 max	0.50–1.00	—	4.0–6.0	0.40–0.70	0.030 max	0.035 max
7CrMoB	0.10 max	0.60 max	0.50–1.00	—	6.0–8.0	0.40–0.70	0.030 max	0.035 max
9CrMoB	0.10 max	0.60 max	0.50–1.00	—	8.0–10.0	0.90–1.20	0.030 max	0.035 max
12CrMoB[a]	0.23 max	0.80 max	0.30–1.00	0.3–0.8	11.0–12.5	0.80–1.20	0.025 max	0.025 max
12CrMoVB[b]	0.23 max	0.80 max	0.30–1.00	—	11.0–13.0	0.80–1.20	0.030 max	0.030 max
12CrMoWVB[c]	0.28 max	0.80 max	0.50–1.00	0.3–0.8	11.0–13.0	0.80–1.20	0.030 max	0.030 max
Ni-steel								
1NiLB	0.07 max	0.60 max	0.30–1.10	0.80–1.20	—	—	0.030 max	0.030 max
2NiLB	0.07 max	0.60 max	0.30–1.10	2.00–2.75	—	—	0.030 max	0.030 max
3NiLB	0.07 max	0.60 max	0.50–1.10	2.80–3.75	—	—	0.030 max	0.030 max
1NiB	0.10 max	0.80 max	0.50–1.20	0.80–1.10	—	—	0.030 max	0.035 max
2NiB	0.10 max	0.80 max	0.50–1.20	2.00–2.75	—	—	0.030 max	0.035 max
3NiB	0.10 max	0.80 max	0.50–1.20	2.80–3.50	—	—	0.030 max	0.035 max
1NiC	0.15 max	0.80 max	0.50–1.20	0.80–1.20	—	—	0.030 max	0.035 max
2NiC	0.15 max	0.80 max	0.50–1.20	2.00–2.75	—	—	0.030 max	0.035 max
Mn–Mo steel								
MnMoB	0.10 max	0.80 max	1.20–1.80	—	—	0.25–0.45	0.025 max	0.025 max
2MnMoB	0.10 max	0.80 max	1.60–2.00	—	—	0.25–0.45	0.025 max	0.025 max
High strength steel								
MnNiB	0.10 max	0.80 max	0.60–1.20	1.00–1.80	—	—	0.030 max	0.035 max
NiMoB	0.10 max	0.80 max	0.80–1.60	1.20–1.90	—	0.20–0.50	0.030 max	0.035 max
1NiMoC	0.18 max	0.80 max	0.50–1.20	1.20–1.90	—	0.20–0.50	0.030 max	0.035 max
2NiCrMoB	0.10 max	0.80 max	1.30–2.20	1.50–2.50	0.70–1.50	0.20–0.50	0.030 max	0.035 max

* Mn:Si at least 2:1. [a] 0.3%V max. [b] 0.5%V max. [c] 0.5%V max: 0.7–1.0%W.

HAZ cracking in ferritic steels is influenced by the following inter-related variables:

1. Steel composition and transformation behaviour.
2. Welding process and type of consumable.
3. Energy input of the welding process, and preheating temperature.
4. Joint restraint.

In general, more highly alloyed steels have a greater tendency to cracking, due to their lower transformation temperature and the formation of harder transformation products. In practice, the important aspects of transformation behaviour of a steel are the hardenability of the steel, and the susceptibility of the hardened structure to cracking.

Both hardenability and susceptibility generally increase with increases in carbon and alloying element content. The dominant effect of carbon has been recognized by the empirical derivation of carbon equivalent (CE) formulae which are intended to describe the weldability of a steel. A widely used formula for carbon–manganese structural steels to BS 4360:1986, is as follows:

$$CE = C + \frac{Mn}{6} + \frac{Cu + Ni}{15} + \frac{Cr + Mo + V}{5}$$

This relationship is recognized by the International Institute of Welding and ISO. The following may be also considered:

$$Pcm = C + \frac{Si}{30} + \frac{Mn + Cu + Cr}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B$$

$$CEN = C + A(C)\left[\frac{Si}{24} + \frac{Mn}{6} + \frac{Cu}{15} + \frac{Ni}{20} + \frac{Cr + Mo + V + Nb}{5} + 5B\right]$$

where

$$A(C) = 0.75 + 0.25 \tanh[20(C - 0.12)]$$

The Pcm formula was derived primarily for higher strength low alloy steels, while the CEN relationship recognizes a non-linear contribution of carbon to hardenability and cracking risk at higher carbon levels. With increased CE, more stringent precautions are necessary to avoid cracking. It should be appreciated that such formulae apply only to the particular compositions used in determining them, and are not universally applicable.

The risk of HAZ cracking is highly dependent upon the hydrogen content of the freshly deposited weld metal. With respect to manual metal arc welding, the risk of cracking in a particular steel is lower when low hydrogen basic electrodes are used rather than the common rutile type, particularly if the former electrodes are dried at temperatures above about 300°C. The submerged-arc and gas-shielded metal-arc processes can produce weld metal deposits having hydrogen contents comparable to or lower than those of basic electrodes, and some relaxation of welding conditions may be possible with these processes, provided that clean dry consumables are used. Typical weld metal hydrogen levels determined following the procedures in BS 6693 are given in Table 33.12.

Table 33.12 TYPICAL HYDROGEN CONTENTS FOR DIFFERENT STEEL WELD METALS

Weld metal type	*Range of hydrogen contents* (ml per 100 g *of deposited metal*)
BS 639:1986 Classification C	70–100
BS 639:1986 Classification R	20–35
BS 639:1987 Classification B (dried 100–150°C)	10–15
BS 639:1986 Classification B (baked 350–450°C)†	3–10
Submerged arc	5*–25
Gas-shielded metal arc (Ar or CO_2)	3*–10
Cored CO_2: basic flux	3–5
rutile flux	5–15

* Lower values for clean, dry consumables.
† Consumable manufacturer's advice on drying conditions should be sought.

Thermal conditions prevailing during welding are controlled for one or both of two reasons. First, by control of the cooling rate, it is often possible to determine the transformation product after welding. Secondly, cracking may be avoided by holding the weld area at about 250 °C (when

the embrittling effect of hydrogen is negligible) for a sufficient length of time for hydrogen to diffuse away from susceptible regions.

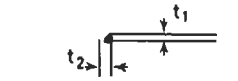
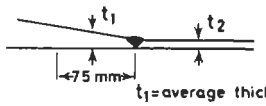
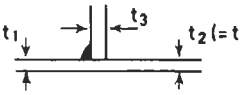
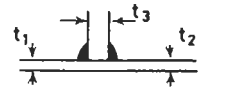
For a given weld geometry, increased heat input during welding will result in a lower cooling rate. In many materials, such reduction in cooling rate will be sufficient to avoid transformation to hard, susceptible microstructures. Increased heat input may be achieved by increasing the welding current or voltage, or by reducing the speed of travel. If cracking cannot be controlled by increasing energy input, preheat may be applied to reduce the cooling rate after welding. The preheat temperature required in a particular case will depend upon the material composition, the joint restraint, and the welding process used, but it will usually be in the range 100–250 °C. In multipass welds, the preheat temperature must be maintained between weld runs as an interpass temperature.

Joint restraint may be defined as resistance to deformation which would relieve contractural welding stresses. Restraint will, in general, increase with increasing thickness of the component parts being joined. Increase in material size will also increase the cooling rate of the weld by affording a larger heat sink. Joint type is significant in determining the number of paths along which heat may be conducted away from the weld, and the effect of joint geometry on cooling conditions can be described by a 'combined thickness' parameter. The combined thickness is the total thickness of material in mm through which heat can flow away from the weld, as indicated in Table 33.13.

When doubt exists regarding the risk of cracking in a given situation, it must be recommended that a procedural trial be undertaken.

It has been found possible with carbon–manganese structural steels to avoid cracking by controlling welding conditions so that the microstructure in the HAZ is not harder than a critical value. When using manual metal arc welding consumables of relatively high hydrogen potential, the HAZ hardness should not exceed 350 HV. With low hydrogen consumables or CO_2 welding, a hardness of 400 HV or even above is appropriate. Figure 33.1 is a nomogram for material of CE determined as above, showing welding conditions such that the critical hardness is not exceeded,

Table 33.13 DETERMINATION OF COMBINED THICKNESS

Type of joint and heat flow	Combined thickness (mm)
	2t
	$t_1 + t_2$
	$t_1 + t_2$
	$t_1 + t_2 + t_3$
	$\frac{1}{2}(t_1 + t_2 + t_3)$

and cracking can be avoided. Allowance is made for the use of processes with different hydrogen potentials, and for the combined thickness of the weldment. From the intended welding process, the relevant CE scale is selected. A vertical line is drawn from the CE of the material being considered, to intersect the intended preheat temperature. From this intersection, a line is taken horizontally to the appropriate combined thickness, and then vertically down to determine the minimum arc energy input necessary during welding to avoid exceeding the critical hardness. Similarly, given a material, thickness and arc energy, the minimum preheat temperature can be determined. Further reference to BS 5135:1984 should be made. One caveat is that the critical hardness to avoid cracking is slightly dependent on carbon equivalent. Conservatism is recommended when applying Figure 33.1 to steels of CE < 0.40 for welds to be made without preheat.

The CE approach for formulating welding procedures is unworkable at CEs above 0.6. With low alloy steels, it is possible to classify susceptibility to HAZ cracking according to their transformation behaviour. Five general classifications are shown in Table 33.14, together with summaries of precautions necessary for avoiding cracking. Appropriate preheat and interpass temperatures for steels in Classes 4 and 5 can be obtained from Figure 33.2. More precise definition of behaviour is not possible since cracking susceptibility is not uniquely related to hardness, while the effect of joint geometry cannot be adequately quantified for these materials.

In general, weld metals used for mild and low alloy steels contain rather less carbon than the parent material, and in consequence are less susceptible to hydrogen-induced cracking than is a HAZ. The factors outlined above for HAZs are nonetheless applicable, and precautions to avoid hydrogen-induced weld metal cracking may be necessary in some cases.

HAZ liquation cracking

Another problem in the welding of ferritic steels is cracking associated with liquation of nonmetallic phases at prior austenite grain boundaries in the HAZ, under the influence of thermal stresses in this area. Susceptibility is dependent mainly on the relative amounts of sulphur, carbon, manganese and phosphorus in the steel and, in plain iron–carbon alloys, the problem becomes significant with carbon contents above about 0.2%. At this carbon content, a manganese to sulphur ratio of at least 20:1 is required to avoid the problem, and with higher carbon contents, this ratio may need to be as high as 30:1 or 50:1.

Table 33.14 CLASSIFICATION OF LOW ALLOY STEELS

Class	*Hardenability*	*Susceptibility to HAZ cracking*	*Examples*	*Precautions in welding*
1	Low	None	Mild steel	None
2	Low	Low	(1) Mild steel with C > 0.15% but < 0.25%, and Mn < 1.0%. (2) C–Mn steels with C < 0.2% and Mn < 1.4%	Thin sections, none; with thicker sections, lower H_2 processes, high heat input and some preheat are all advantageous
3	Low	High (twinned martensite)	Medium carbon steels, e.g. 080M30, 080M40*	Production of non-martensitic HAZ more important than low hydrogen. Use high heat inputs, and 250–350 °C preheat
4	High	Low (low carbon martensite)	Low carbon, low alloy high strength steels, e.g. 9%Ni HY80, C–Mn steels in thick sections	Low hydrogen processes, increased heat input and some preheat generally necessary
5	High	High (twinned martensite or bainitic constituents)	(1) Medium carbon alloy steels, e.g. 530H32, 835M30* (2) Some creep resistant steels, e.g. 5Cr ½Mo, 2¼Cr 1Mo	Preheat and interpass temperature in the range 200–350 °C. (May be possible to use 150 °C in thin sections.) Post-weld heat treatment advisable

For further information, see T. Boniszewski and R. G. Baker. Proc. Second Commonwealth Welding Conference. Institute of Welding, London. 1965, Paper M5.

* BS 970:Part 1:1983.

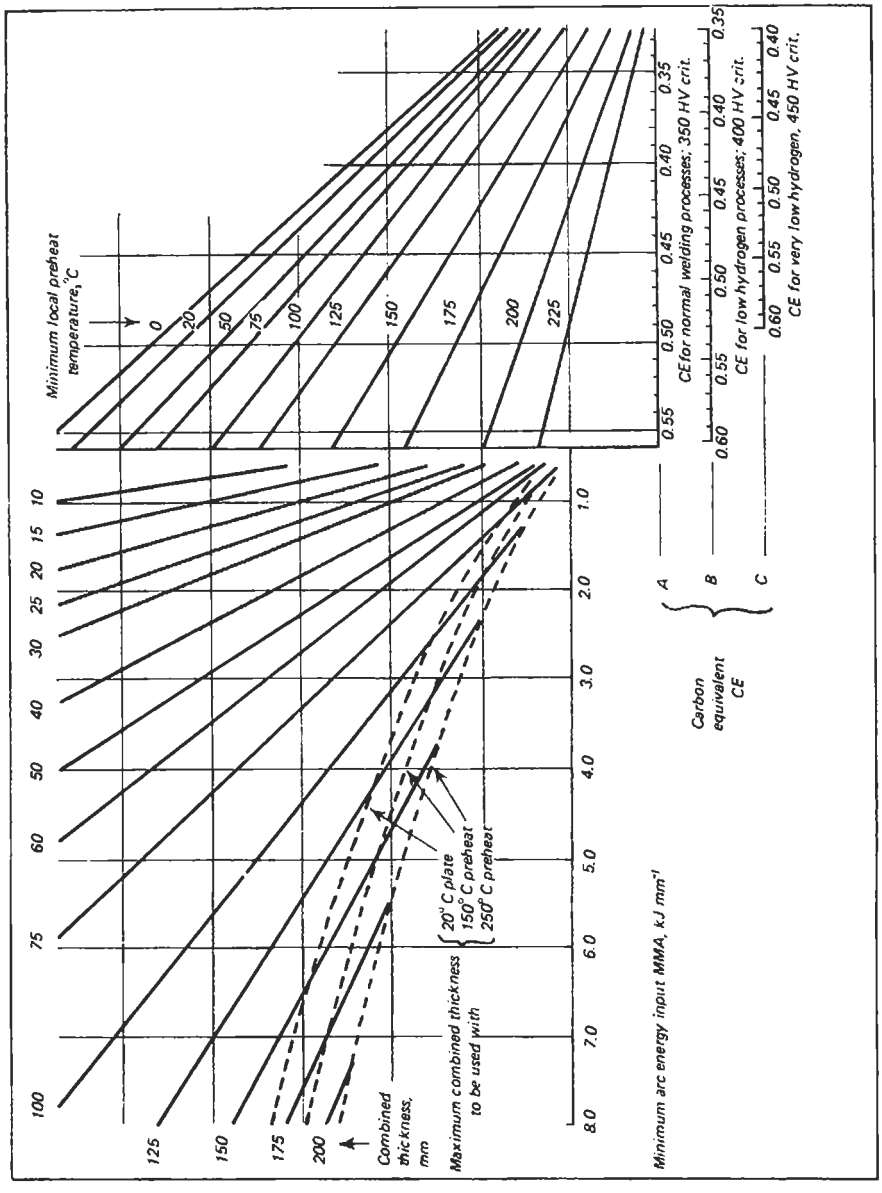


Figure 33.1 *Welding conditions for mild and* C–Mn *steels*

For further information, *see* N. Bailey, *Met. Constr. & Brit. Weld J.*, 1970, **2**, 442.
CE Scale A: Normal welding processes; HAZ hardness restricted to below 350 HV.
CE Scale B: Low hydrogen welding processes; HAZ hardness restricted to below 400 HV.
CE Scale C: Very low hydrogen welding processes; HAZ hardness restricted to below 450 HV.

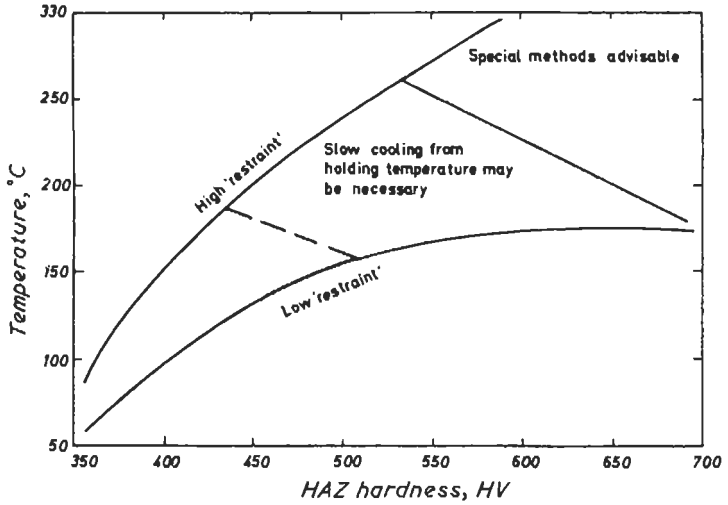


Figure 33.2 *Suggested preheat conditions for procedural tests for steels in Classes 4 and 5 of Table 33.14.*

Lamellar tearing

Lamellar tearing may arise in joints in which the fusion boundary of the weld is parallel to the plate surface, and tensile residual stresses act across the plate thickness. Cracking is generally step-like in character, and is associated with inclusions which are rolled into planar form during plate manufacture. Such inclusions result in reduced ductility in the through-thickness direction of the plate. Lamellar tearing will not normally arise in plate with a through-thickness ductility above 20% reduction in area (RA). Between 10 and 20% RA, it may be encountered in highly restrained cases, such as fully penetrating nozzles. If the ductility is below 10% RA, cracks may form even in relatively lightly restrained T-joints. Lamellar tears have been found in plate of 10 to 175 mm thickness, but are not common below 25 mm thickness. Where experience with a particular material and joint configuration indicates a risk of lamellar tearing, consideration must be given to joint design and welding procedure to reduce the effect of restraint, and to ensure that the fusion boundary of the weld runs across possible planes of weakness in the material.

Stress relief cracking

A number of ferritic steels may be subject to stress relief, or reheat, cracking. Cracking is intergranular, and occurs in the HAZ when restrained joints are given a post-weld heat treatment. The problem is analogous to that in austenitic steels considered below, and arises primarily in alloys showing secondary hardening. Cracking behaviour cannot be predicted at the present time with any precision. Cracking has not been reported in alloys such as $2\frac{1}{4}$Cr/1Mo or $\frac{1}{2}$Mo/B steels at below 75 mm thickness, or in $\frac{1}{2}$Cr/$\frac{1}{2}$Mo/$\frac{1}{4}$V at below 18 mm thickness. The risk of cracking can be reduced by weld dressing to reduce local stress concentrations, and by controlled heat treatment procedures.

HIGH ALLOY HEAT AND CORROSION-RESISTANT STEELS

These fall into three basic categories: the martensitic chromium-containing steels, the higher chromium ferritic steels and the chromium–nickel austenitic steels. With different chromium and nickel contents, materials containing mixtures of the three main microstructural consituents may be produced. The welding behaviour of such materials is generally dependent on the major phase present.

MARTENSITIC STAINLESS STEELS

The principal problem with the martensitic alloys is that of hydrogen-induced cold cracking, as with low alloy steels. Preheating is required, generally to over 200 °C, followed by slow cooling and post-weld heat treatment at 650–750 °C. The likelihood of cracking depends on a number of factors, and procedural trials are normally required to determine the optimum welding conditions in any given instance. Carbon content is of particular importance, and thin plate material of less than 0.1% carbon can often be welded without preheat or post-weld heat treatment; with thicker material or carbon content above 0.2%, both preheat and heat treatment are necessary. At higher carbon levels, it is essential that the welds do not cool to room temperature between completion of welding and application of heat treatment (although the joint should cool sufficiently for complete transformation to martensite to occur in the HAZ, prior to heat treatment), unless sufficient time is given to permit hydrogen diffusion out of the weld area. The martensite transformation finish temperature (M_f) may not be well defined, and in such cases, a suitable cool-out temperature should be defined by procedural tests. Suggested welding conditions for typical alloys are given in Table 33.15. If matching composition consumables are required (e.g. Table 33.16), careful consideration to hydrogen-induced weld metal cracking should be paid, and adequate electrode baking is essential. The use of austenitic consumables is preferred. Although these are of lower strength than the parent material, hydrogen is more soluble in austenite than in martensite, and thus hydrogen tends to remain in the weld metal, reducing the risk of cracking. Manual metal arc welding is generally employed for martensitic stainless steels, with TIG welding finding application for thin gauge material.

Table 33.15 SUGGESTED WELDING CONDITIONS FOR 13% CR STEELS

	Temperature, °C		
Material	*Preheat*	*Interpass*	*Post-weld heat treatment*
13%Cr/0.1%C	250	250–350	700–750
13%Cr/0.2%C	250	250–350	700–750
13%Cr/4%Ni/0.06%C	150	150–250	600–650

FERRITIC STAINLESS STEELS

Ferritic stainless steels suffer embrittlement on welding due to grain growth and grain boundary martensite formation in the heat affected zone that is heated above 1100 °C. These materials are notch sensitive, and the grain growth raises the ductile–brittle transition temperature to above room temperature, resulting in a brittle joint when the weldment cools out. Preheat to 200 °C and post-heat treatment at 750–850 °C are recommended. These measures do not avoid the deleterious microstructure, but serve to reduce residual welding stresses as far as possible and obtain some HAZ softening. The toughness of matching composition weld metal (e.g. Table 33.16) may be lower than that of the heat affected zone. Thus, austenitic consumables are preferred unless differences in coefficient of expansion between the weld metal and parent material are likely to cause thermal fatigue in service. Manual metal arc and TIG welding are most commonly used for ferritic grades of stainless steel.

Ferritic stainless steels are also sensitive to intercrystalline corrosive attack in the region around a weld that is heated to above 1100 °C. The problem may be avoided by post-weld heat treatment at between 700 and 850 °C. In some circumstances sigma phase may form during heat treatment, causing brittleness below 200 °C. This can be eliminated by annealing at above 850 °C.

The problems of loss of toughness and corrosion resistance in the weld area restrict the industrial use of fusion welded ferritic stainless steel assemblies. These materials can, however, offer good general corrosion resistance, and are considerably more resistant to chloride-induced stress corrosion than are austenitic grades. To avoid the welding problems of conventional ferritic stainless steels, alloys have been developed based either on reduction in interstitial elements, or on balanced chromium–nickel contents so that mixed ferrite–martensite or ferrite–austenite microstructures are obtained. Such materials have been successfully welded in thin gauges for service conditions where a risk of stress corrosion has precluded the use of austenitic steels.

Table 33.16 MANUAL METAL ARC WELDING ELECTRODES FOR Cr AND Cr/Ni STEELS (BS 2926:1984)

Composition code	*Element* wt %						
	C	Si	Mn	Cr	Ni	Mo	Nb
13	0.08 max	1.0 max	1.0 max	11.0–13.5	0.60 max	0.5 max	0.5 max
13.4Mo	0.06 max	1.0 max	1.0 max	11.0–13.5	4.0–5.0	0.4–0.7	
17	0.10 max	1.0 max	1.0 max	15.0–18.0	0.60 max	0.5 max	
28	0.10 max	1.0 max	1.0 max	26.0–32.0	0.60 max	0.60 max	0.5 max
19.9	0.08 max	1.0 max	0.5–2.5	18.0–21.0	9.0–11.0	0.5 max	
19.9.L	0.04 max	1.0 max	0.5–2.5	18.0–21.0	9.0–11.0	0.5 max	
19.9.3	0.10 max	1.0 max	0.5–3.0	18.5–21.0	8.0–10.0	2.0–4.0	
19.9.Nb	0.10 max	1.0 max	0.5–2.5	18.0–21.0	9.0–11.0	0.5 max	10 × C – 1.10
17.8.2	0.06–0.10	0.8 max	0.5–2.5	16.5–18.5	8.0– 9.5	1.5–2.5	
19.12.2L	0.04 max	1.0 max	0.5–2.5	17.0–20.0	11.0–14.0	2.0–2.5	
19.12.3	0.08 max	1.0 max	0.5–2.5	17.0–20.0	10.0–14.0	2.5–3.5	
19.12.3.L	0.04 max	1.0 max	0.5–2.5	17.0–20.0	10.0–14.0	2.5–3.5	
19.12.3Nb	0.10 max	1.0 max	0.5–2.5	17.0–20.0	10.0–14.0	2.5–3.5	10 × C – 1.10
19.13.4	0.08 max	1.0 max	0.5–2.5	17.0–20.0	11.0–15.0	3.5–5.5	
19.13.4.L	0.04 max	1.0 max	0.5–2.5	17.0–20.0	11.0–15.0	3.5–5.5	
19.13.4.Nb	0.10 max	1.0 max	0.5–2.5	17.0–20.0	11.0–15.0	3.5–5.5	10 × C – 1.10
18.15.3LNb*	0.04 max	1.0 max	0.5–7.0	16.0–20.0	13.0–18.0	2.0–3.5	
23.12	0.15 max	1.0 max	0.5–2.5	22.0–25.0	11.0–14.0	0.5 max	
23.12L	0.04 max	1.0 max	0.5–2.5	22.0–25.0	11.0–14.0	0.5 max	
23.12.Nb	0.10 max	1.0 max	0.5–2.5	22.0–25.0	11.0–14.0		10 × C – 1.10
23.12.2	0.10 max	1.0 max	0.5–2.5	22.0–25.0	11.0–14.0	2.0–3.0	
23.12.W[a]	0.20 max	1.0 max	0.5–2.5	22.0–25.0	11.0–14.0		
25.6.2*	0.06 max	1.0 max	0.5–2.5	24.0–28.0	4.0– 8.0	1.5–4.0	
25.6.2Cu*[b]	0.06 max	1.0 max	0.5–2.5	24.0–28.0	4.0– 8.0	1.5–4.0	
25.20	0.20 max	0.7 max	0.5–6.0	24.0–28.0	18.0–22.0	0.5 max	
25.20.H	0.35–0.45	0.7 max	0.5–2.0	24.0–28.0	18.0–22.0	0.5 max	
25.20.Nb	0.12 max	0.7 max	0.5–6.0	24.0–28.0	18.0–22.0	0.5 max	10 × C – 1.20
25.20.1	0.12 max	0.7 max	0.5–2.5	25.0–28.0	18.0–22.0	0.5–1.20	
25.20.1Nb	0.12 max	0.7 max	0.5–6.0	24.0–28.0	18.0–22.0	0.1–1.20	10 × C – 1.20
25.20.2	0.12 max	0.7 max	0.2–2.5	25.0–28.0	18.0–22.0	2.0–3.0	
25.21.2LMn*	0.04 max	1.0 max	3.0–7.0	23.0–27.0	19.0–23.0	2.0–3.0	
15.35H	0.25–0.50	1.0 max	1.0–2.5	14.0–20.0	33.0–40.0	0.5 max	
20.25.5LCuNb[c]	0.04 max	1.0 max	0.5–4.0	19.0–22.0	24.0–28.0	4.0–5.5	8 × C – 0.5
20.34.2CuNb[d]	0.07 max	0.6 max	0.5–2.5	19.0–21.0	32.0–36.0	2.0–3.0	8 × C – 1.0
25.35H	0.35–0.45	1.0 max	0.5–2.0	23.0–27.0	32.0–36.0	0.5 max	
25.35HNb	0.35–0.45	1.0 max	0.5–2.0	23.0–27.0	32.0–36.0	0.5 max	0.5–1.8
29.9	0.15 max	1.2 max	0.5–2.5	28.0–32.0	8.0–12.0	0.5 max	
29.9.1	0.15 max	1.0 max	0.5–2.5	28.0–32.0	8.0–10.5	0.5–1.20	
29.9.2	0.15 max	1.0 max	0.5–2.5	28.0–32.0	8.0–10.5	2.0–3.0	

Notes: All grades 0.030%S max and 0.040%P max.

* 0.25%N max. [a] 2.0–4.0%W. [b] 1.0–4.0%Cu. [c] 1.0–2.5%Cu. [d] 3.0–4.0%Cu.

AUSTENITIC STAINLESS STEELS

For practical purposes, austenitic stainless steels can be regarded as among the most weldable materials, and virtually any process can be used to make a joint. The manual metal arc and TIG processes are most common, with MIG and submerged arc welding being used when high deposition rates are required. Manual metal arc and gas-shielded welding consumables are given in Tables 33.16 and 33.17. Oxyacetylene welding is readily carried out with consumables as in Table 33.18, but is not preferred since excessive heating and a carburizing flame can cause weld decay, as considered below. A flux is desirable, and a neutral flame is recommended, oxidizing conditions causing porosity.

Table 33.17 FILLER RODS AND WIRES FOR GAS-SHIELDED ARC WELDING OF AUSTENITIC STAINLESS STEELS (BS 2901: PART 2:1983)

	Element wt %						
Type	C	Si	Mn	Ni	Cr	Mo	Nb
308S92	0.03 max	0.25–0.65	1.0–2.5	9.0–11.0	19.5–22.0	0.5 max	—
308S96	0.08 max	0.25–0.65	1.0–2.5	9.0–11.0	19.5–22.0	0.5 max	—
308S93	0.03 max	0.65–1.00	1.5–2.5	9.5–10.5	20.0–21.0	0.5 max	—
347S96	0.08 max	0.25–0.65	1.0–2.5	9.0–11.0	19.0–21.5	0.5 max	10 × C – 1.0
309S94	0.12 max	0.25–0.65	1.0–2.5	12.0–14.0	23.0–25.0	0.5 max	—
309S92	0.03 max	0.25–0.65	1.0–1.5	12.0–14.0	23.0–25.0	0.5 max	—
311S94	0.12 max	0.25–0.65	1.0–2.5	12.0–14.0	23.0–25.0	0.5 max	10 × C – 1.3
310S94	0.08–0.15	0.25–0.65	1.0–2.5	20.0–22.5	25.0–28.0	0.5 max	—
310S98	0.35–0.45	0.80–1.30	1.0–2.5	20.0–22.5	25.0–28.0	0.5 max	—
312S94	0.15 max	0.25–0.65	1.0–2.5	8.0–10.5	28.0–32.0	0.5 max	—
313S94	0.06–0.13	0.25–0.65	1.0–2.5	20.0–22.5	25.0–28.0	—	10 × C – 1.3
316S92	0.03 max	0.25–0.65	1.0–2.5	11.0–14.0	18.0–20.0	2.0–3.0	—
316S96	0.08 max	0.25–0.65	1.0–2.5	11.0–14.0	18.0–20.0	2.0–3.0	—
316S93	0.03 max	0.65–1.00	1.5–2.5	10.0–13.5	18.0–20.0	2.5–3.0	—
317S96	0.08 max	0.25–0.65	1.0–2.5	13.0–15.0	18.5–20.5	3.0–4.0	—
318S96	0.08 max	0.25–0.65	1.0–2.5	11.0–14.0	18.0–20.0	2.0–3.0	10 × C – 1.0

S and P each to be 0.030% max, Cu 0.5% max.

Table 33.18 FILLER RODS FOR THE GAS WELDING OF AUSTENITIC STAINLESS STEELS (BS 1453: 1972)

	Element wt %						
Type	C	Si	Mn	Ni	Cr	Mo	Nb
347S96	0.08 max	0.25–0.60	1.0–2.5	9.0–11.0	19.0–21.5	—	10 × C–1.0
309S94	0.12 max	0.25–0.60	1.0–2.5	12.0–14.0	23.0–25.0	—	—
311S94	0.12 max	0.25–0.60	1.0–2.5	12.0–14.0	23.0–25.0	—	10 × C–1.3
310S94	0.08–0.15	0.25–0.60	1.0–2.5	20.0–22.5	25.0–28.0	—	—
313S94	0.06–0.13	0.25–0.60	1.0–2.5	20.0–22.5	25.0–28.0	—	10 × C–1.3
316S96	0.08 max	0.25–0.60	1.0–2.5	11.0–14.0	18.0–20.0	2.0–3.0	—
318S96	0.08 max	0.25–0.60	1.0–2.5	11.0–14.0	18.0–20.0	2.0–3.0	10 × C–1.0

S and P each to be 0.030% max

The main metallurgical problems with austenitic stainless steels are the avoidance of weld metal and heat affected zone cracking, and maintenance of full corrosion resistance in the weld area.

Fully austenitic weld metals are susceptible to cracking both during solidification and in underlying reheated runs. The problem may be entirely avoided by the use of consumables with composition such that the deposited weld metal contains more than about 3–5% ferrite. A guide to the relationship between composition and structure is given by the Schaeffler diagram, reproduced in Figure 33.3. Dilution from parent material must be taken into account when using the Schaeffler diagram.

The presence of ferrite in the weld metal may promote transformation to the embrittling sigma phase during heat treatment or in service at temperatures between 550 and 850 °C. The compositional range likely to suffer rapid embrittlement is indicated in Figure 33.3. Particularly if sigma formation is a hazard, the preferred weld metal compositions lie in the shaded area.

In certain corrosion-resistant applications, notably urea plant, the presence of ferrite may be undesirable since it can lead to preferential attack taking place on the weld metal. In such cases, low or zero ferrite consumables should be used, and the risk of cracking controlled by minimizing joint restraint and welding with minimum heat input. Increased manganese contents of 3–5% are beneficial.

During the welding cycle, intergranular precipitation of chromium-rich carbides can occur in areas heated to within 500–900 °C. This precipitation causes local loss of chromium from the

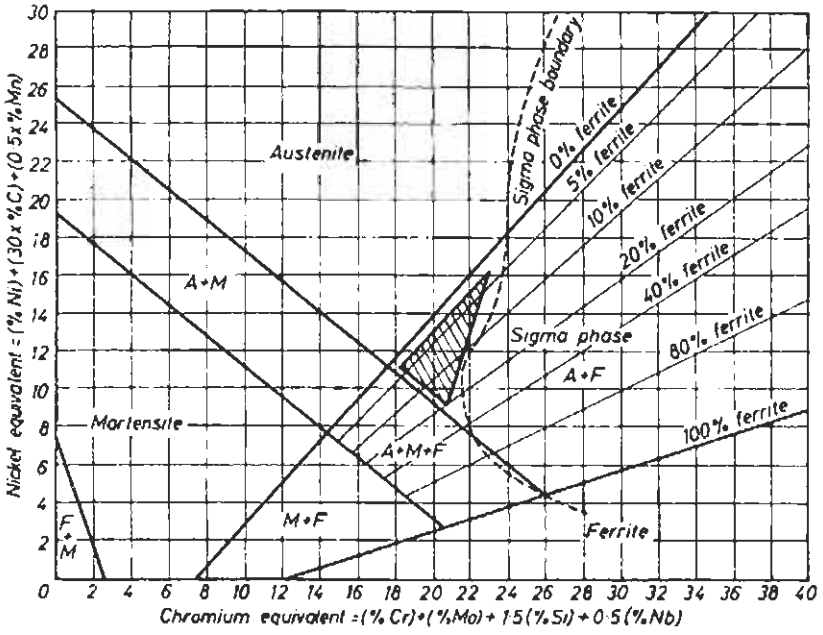


Figure 33.3 *Modified Schaeffler diagram for constitution of stainless steel weld metal.*

matrix, with a consequent reduction in corrosion resistance and susceptibility to intercrystalline attack, or 'weld decay'. The problem is normally avoided by the use of material either with carbon contents below 0.03%, or containing strong carbide forming elements such as niobium or titanium. Such 'stabilized' steels are not immune to intercrystalline attack under all circumstances, and heat treatment within the sensitizing range 500–900 °C can induce sensitization to intercrystalline corrosion. If post-weld heat treatment is carried out, the temperature should be above 900 °C. For practical purposes, intercrystalline attack due to arc welding is unlikely to be encountered in unstabilized molybdenum-free material of 0.06% carbon and below, provided that the arc energy per unit length of weld metal is below 2 kJ mm^{-1}, although service in highly oxidizing media should be regarded with caution.

Austenitic steels may suffer HAZ liquation cracking during welding. The problem is minimized by the use of low arc energy welding conditions and with wrought material, by avoiding grain sizes coarser than about ASTM 3–4. In castings, cracking can often be suppressed by using material containing above 5% ferrite. The liquation cracks are of the order of 0.5 mm long, and are not generally significant in service. In welds of high restraint, however, they can form initiation points for 'reheat cracking' during elevated temperature service or post-weld heat treatment. At elevated temperature, intragranular strain-induced precipitation occurs in the HAZ. This causes a loss of creep ductility, and if joint restraint is high enough, intergranular cracking results. All common grades of austenitic stainless steel are susceptible to reheat cracking, with the exception of the 18%Cr/12%Ni/3%Mo types, provided that these do not contain residual carbide forming elements such as niobium or titanium. The risk of reheat cracking is reduced by dressing weld toes to remove liquation cracks, by the use of low hot strength weld metal, and by stress relief at above 950 °C.

High proof stress variants of the common austenitic stainless steels have been developed, based either on solid solution hardening by nitrogen or on 'warm working' by rolling at down to 850 °C to obtain a work hardening effect. These materials can generally be welded with normal consumables with no loss of strength in the weld area. With the nitrogen-bearing steels, excessive dilution of the weld pool by parent material causes a fully austenitic weld metal, with a risk of solidification cracking. High dilution situations, such as the root pass of a butt weld in thick plate, should therefore be regarded with caution. Joint preparation should be such that at least 50% of the molten weld pool is filler material.

CLAD STEELS

These consist of mild or low alloy steel clad with an overlay by rolling, explosively or by weld deposition. A number of overlays such as nickel, Monel, Inconel or stainless steel are available, to fulfil different requirements.

Various welding processes may be used for joining clad plate, although manual metal arc welding is normally employed in view of the range of electrodes available, and the facility of control. The recommended procedure is to prepare the ferritic side of the joint, and weld this conventionally with suitable electrodes, taking care that no cladding material is picked up by the weld metal. The clad side is then chipped out to sound metal to below the depth of the cladding, and welded using suitable filler metal. The choice of consumable for this weld is determined primarily by the necessity to accept dilution from the ferritic substrate material, and give the desired final weld metal composition without the formation of undesirable microstructures. A two-pass technique is usually specified, the first pass employing a consumable tolerant of dilution, and the second pass being intended to deposit weld metal of matching composition to the cladding. Typical consumable compositions are given in Table 33.19.

CAST STEELS

The welding of cast steels presents no special problems additional to those encountered in wrought metal of similar composition. Silicon and manganese contents are usually high, and this has an influence on weldability. Repairs to steel castings are usually subject to the same conditions of restraint as repairs to cast iron, and preheating is often desirable for this reason alone. Plain carbon steels with less than 0.25% C may otherwise be welded without preheat following the procedure in Figure 33.1. For steels containing 0.25–0.50% C, preheat temperatures up to 300 °C may be used, while for steels of carbon content greater than 0.50%, a preheat of 300 °C and a post-weld stress relief at 650 °C should be employed. It may be necessary to use nickel-bearing electrodes when carbon contents are very high. Alternatively, bronze welding may be used.

Preheating, when recommended, should preferably be applied to the whole casting and the figures in Table 33.20 should be regarded as minima. Manual metal arc welding is normally employed, although other methods are possible.

Table 33.19 MANUAL METAL ARC WELDING ELECTRODE COMPOSITIONS FOR WELDING CLAD STEELS ON THE CLADDING SIDE

Cladding	*Electrode*	
	First pass to cover steel	*Remaining passes*
Austenitic stainless steel	25Cr/12Ni	Matching composition to cladding
Chromium stainless steel	25/12	25/12 or matching composition to cladding
Nickel	Nickel 141	Nickel 141
Monel 400	Monel 190	Monel 190
Inconel 600	Inconel 182	Inconel 182

Table 33.20 MANUAL METAL ARC WELDING PROCEDURES FOR A SELECTION OF CAST STEELS

Steel type	*Specification*	*Electrode*	*Preheat °C*	*Post-heat °C*
0.25%C max	BS 592:1967—Grade A	BS 638:1986 E43XXR‡	20–150§	600–650*
0.35%C max	BS 592:1967—Grade B	BS 639:1986 E51XXB	20–150§	600–650
0.45%C max	BS 592:1967—Grade C	BS 639:1986 E51XXB	20–150§	600–650
C/0.5% Mo	BS 1398:1967—Grade A	BS 2493:1985—MoB	150	630–680
2.25%Cr/0.5%Mo	BS 1504–622	BS 2493:1985—2CrMoB	275	640–690†
9%Cr/1%Mo	BS 1463:1967	BS 2926:1984—23.12	250	650–720†
13%Cr	BS 1630:1967—Grade A	BS 2926:1984—23.12	250	680–750†
18%Cr/8%Ni/Nb	BS 1631:1967—Grade B	BS 2926:1984—19.9.Nb	None	None
18%Cr/8%Ni/Mo	BS 1632:1967—Grade B	BS 2926:1984—19.12.3	None	None

* Desirable, but not essential.
† Immediate post-weld heat treatment and special care essential.
‡ Select electrode to match casting properties.
§ *See* Figure 33.1

CAST IRONS

Malleable irons, grey iron, spheroidal graphite cast irons and austenitic cast irons may be welded, provided suitable precautions are taken.

Difficulties are due to lack of ductility in the parent material to accommodate weld shrinkage stresses, the transfer of carbon to the weld metal, resulting in hard, brittle deposits, and hardening in the heat affected zone. In addition, high sulphur contents may result in hot shortness in the weld and subsequent cracking.

Spheroidal graphite irons and other alloy cast irons have increased ductility and impact resistance over normal grey iron, and so may be welded with rather less difficulty. White cast irons can seldom be welded satisfactorily.

Table 33.21 FILLER RODS FOR GAS WELDING CAST IRON (BS 1453:1972)

Type	*Element wt %*						
	C	Si	Mn	Ni	S	P	*Applications*
B1	3.0–3.6	2.8–3.5	0.5–1.0	—	0.15 max	1.5 max	Easy machining
B2	3.0–3.6	2.0–2.5	0.5–1.0	—	0.15 max	1.5 max	Hard (valve seats)
B3	3.0–3.5	2.0–2.5	0.5–1.0	1.25–1.75	0.10 max	0.50 max	Ni cast iron

The choice of process is influenced by the type of component and its composition, gas welding and braze welding being suitable for light components, and metal arc and bronze welding for the heavier types of construction. Filler rods for gas welding are given in Table 33.21. For braze welding, consumables C4, C5, or C6 in Table 33.28 may be used. Types of electrodes for manual metal arc and bronze welding are given in Table 33.22.

Table 33.22 ELECTRODES FOR METAL ARC AND BRONZE WELDING OF CAST IRON

Electrode type	*Applications and remarks*
High nickel	Minimum preheat, easily machined. Not for high sulphur irons
60% nickel, 40% iron	Suitable for spheroidal graphite irons. Moderate machineability
Cast iron (soft iron)	General purpose, preheat essential
Austenitic stainless	Austenitic castings
Phosphor bronze	Not affected by sulphur, poor machineability
Aluminium bronze	Good strength, wear resistance and machineability

To accommodate shrinkage stresses and to minimize hardening in the heat affected zone, preheating to 550°C and slow cooling is essential unless minimum penetration techniques are employed. In the latter case, repairs in thin sections may be made using high nickel, nickel–iron or bronze electrodes; and in heavy sections, buttering of the edges of the joint with nickel–iron alloy should be followed by welding with soft iron electrodes. If preheating is not employed, minimum heat input is essential, by the use of short weld runs and small diameter electrodes.

33.5.2 Non-ferrous metals

ALUMINIUM AND ALUMINIUM ALLOYS

The main processes for fusion welding this group of materials are the TIG and MIG systems. Manual metal arc and oxyacetylene welding find very limited application, and then only when alternative processes are not available.

The gas-shielded MIG and TIG processes may be used for all the weldable alloys. Sound joints with good mechanical properties can be obtained, as long as weld cleaning is carefully carried out. TIG is suitable for sheet metal work, butt welds up to 6 mm thick and fillet welds where runs are short. It is also valuable in cases where the edge preparation permits autogenous welding to be used. MIG welding is particularly suitable for fillet welding and for the butt welding of material 5 mm thick and above. MIG welding normally employs commercial purity argon as a shielding gas. This gas is also general for TIG welding, although in sections above 6 mm thickness, helium may offer advantages in increased penetration and travel speed.

The majority of aluminium alloys may be welded without difficulty, provided the correct filler wire is used. Recommendations for all processes are given in Table 33.23, and consumable compositions are in Table 33.24. Certain wrought (and cast) alloys, notably aluminium–$2\frac{1}{4}$% magnesium, aluminium–magnesium silicide and duralumin types, suffer from hot cracking when welded with parent metal fillers and such fillers should be used only under closely controlled conditions of low restraint. The fusion welding of the latter types of alloy is not recommended.

Table 33.23 FILLER WIRES AND ELECTRODES FOR WELDING WROUGHT Al ALLOYS TO BS 1470-1477

Parent material		*Filler wire or electrode*[1]		
Designation	*Type*	*Gas welding*[2]	*MIG or TIG*[3]	*Metal arc*[4]
1080A	99.8%Al	1050A	1080A (1050A)	99.5%Al
1050A	99.5%Al	1050A	1050A	99.5%Al
1200	99.0%Al	1260	1050A	99.5%Al
3103	Al–Mn	3103	3103	Al–Mn
3105	Al–Mn–Mg	3103	3103	—
5251 5154A[5]	Al–Mg	5356	5356 (5056A, 5183, 5556A)	—
5454	Al–Mg	5554	5554	—
5083	Al–Mg–Mn	5356	5556A	—
6063 6061 6082 6060 6463[6]	Al–Mg–Si	4043A (4047A)	4043A (4047A, 5356)	Al–5%Si, Al–10%Si
2014A 2024 2618A 2031	Al–Cu–Mg–Si	NR[7] (4047A)	NR[7] (4047A)	NR[7] (Al–10%Si)

[1] Recommended fillers given first, and alternatives in parentheses.
[2] Fillers to BS 1453:1972:amended 1987.
[3] Filler wires to BS 2901:Part 4:1983.
[4] These are not covered by a British Standard.
[5] These Al–Mg alloys may be susceptible to hot cracking.
[6] 5356 may be used with care to weld these alloys, especially when anodizing is to be carried out, to give a better colour match.
[7] These are not recommended as weldable alloys but 4047A gives the best chance of success.

ALUMINIUM CASTINGS

For welding heat treatable castings, the choice of filler wire should be based upon the composition of the casting itself if post-weld heat treatment is to be employed. If cracking is encountered, a higher alloy content in the filler wire may be required. Alloys containing zinc are generally difficult to weld. For welding LM6, LM9 and LM20, as in BS 1490:1970, 4047A wire may be used: 4043A is recommended for LM18 and LM25, while 5356 and 5556A can be used for LM5 and LM10. Parent material is suggested for the remainder of the weldable materials.

DISSIMILAR ALUMINIUM ALLOYS

Welding different aluminium alloys together frequently involves a compromise between mechanical or corrosion properties and joint soundness. Recommendations are given in Table 33.25a, b and c.

Table 33.24 FILLER RODS AND WIRES FOR THE GAS-SHIELDED WELDING OF ALUMINIUM ALLOYS (AFTER BS 2901:PART 4:1983)

	Element wt %									
Type	Al	Cu	Mg	Si	Fe	Mn	Zn	Cr	Ti	*Notes*
1080A	99.8 min	0.03 max	0.02 max	0.15 max	0.15 max	0.02 max	0.06 max		0.02 max	Cu + Si + Fe + Mn + Zn: 0.2% max
1050	99.5 min	0.05 max	0.05 max	0.25 max	0.40 max	0.05 max	0.07 max		0.05 max	Cu + Si + Fe + Mn + Zn: 0.5% max
3103*	Remainder	0.1 max	0.30 max	0.50 max	0.7 max	0.9–1.5	0.20 max	0.10 max		Si content should be less than that of Fe
4043A	Remainder	0.30 max	0.20 max	4.5–6.0	0.6 max	0.15 max	0.10 max		0.15 max	Cr + Ti*: 0.2% max
4047A	Remainder	0.30 max	0.10 max	11.0–13.0	0.6 max	0.15 max	0.20 max		0.15 max	
5154A	Remainder	0.10 max	3.1–3.9	0.5 max	0.50 max	0.1 –0.5	0.20 max	0.25 max	0.2 max	Mn + Cr: 0.5% max
5554	Remainder	0.10 max	2.4–3.0	0.25 max	0.40 max	0.50–1.0	0.25 max	0.05–0.20	0.05–2.00	Si + Fe: 0.40% max
5056A	Remainder	0.10 max	4.5–5.6	0.40 max	0.50 max	0.10–0.6	0.20 max	0.20 max	0.2 max	Mn + Cr: 0.1–0.5%
5556A	Remainder	0.10 max	5.0–5.5	0.25 max	0.40 max	0.6 –1.0	0.2 max	0.05–0.20	0.05–0.20	Si + Fe: 0.40% max
5356	Remainder	0.10 max	4.5–5.5	0.25 max	0.40 max	0.05–0.20	0.10 max	0.05–0.20	0.06–0.20	
5183	Remainder	0.10 max	4.3–5.2	0.40 max	0.40 max	0.5 –1.0	0.25 max	0.05–0.25	0.15 max	

* Ti content can include other grain refining elements.

Table 33.25a PARENT METAL GROUPS USED IN TABLE 33.25c

Parent metal	*Alloys*
1XXX series	1080A, 1050A, 1200, 1350, LMO*
2XXX series	2014A, 2024, 2618A
3XXX series	3103, 3105
5XXX series	5251, 5454, 5154A
6XXX series	6063, 6061, 6082, 6101A
Al–Si castings	LM6, LM9, LM18, LM20, LM25
Al–Mg castings	LM5, LM10

* Included in this group for simplicity.

Table 33.25b FILLER METALS GROUPS USED IN TABLE 33.25c

Filler metal group	*Alloys*
Pure Al	1080A, 1050A
Al–Si	4043A, 4047A*
Al–Mg	5056A, 5356, 5556A, 5183

* 4047A is used to prevent weld metal cracking in joints of high dilution and restraint. In most other cases, 4043A is preferable.

Table 33.25c SELECTION OF FILLER ALLOYS FOR GAS SHIELDED ARC WELDING MATCHING AND DISSIMILAR ALUMINIUM ALLOYS

Parent metal combination	*Al–Si castings*	*Al–Mg castings*	*3XXX*	*2XXX*	*1XXX*	*7020*	*6XXX*	*5005*	*5XXX*	*5083*
5083	NR[1]	Al–Mg	Al–Mg	NR[2]	Al–Mg	556A	Al–Mg	Al–Mg	Al–Mg	5556A
5XXX	NR[1]	Al–Mg	Al–Mg	NR[2]	Al–Mg	Al–Mg	Al–Mg	Al–Mg[3]	Al–Mg[3]	
5005	Al–Si	Al–Mg	Al–Si	NR[2]	Al–Si	Al–Mg	Al–Si	Al–Mg[3]		
6XXX	Al–Si	Al–Mg	Al–Si	NR[2]			Al–Si or Al–Mg[4]			
7020	NR[1]	Al–Mg	Al–Mg	NR[2]	Al–Si	Al–Mg				
1XXX	Al–Si	Al–Mg	Al–Si	NR[2]	Al–Mg	5556A				
2XXX	NR[2]	NR[2]	NR[2]	NR[2]	Pure Al[5]					
3XXX	Al–Si	Al–Mg	3103[4]							
Al–Mg castings	NR[1]	Al–Mg								
Al–Si castings	Al–Si									

NR = not recommended.

[1] The welding of alloys containing approximately 2% or more of Mg with Al–Si filler metal (and vice-versa) is not recommended because sufficient Mg_2Si precipitate is formed at the fusion boundary to embrittle the joint.

[2] 2XXX alloys covered by British Standards are not regarded as weldable alloys, but 4047A gives the best chance of success.

[3] The corrosion behaviour of weld metal is likely to be better if its alloy content is close to that of the parent metal and not markedly higher. For service in potentially corrosive environments it is preferable to weld 5154A with 5154A filler metal or 5454 with 5554 filler metal. This may only be possible at the expense of weld soundness.

[4] Al–Si gives better crack resistance; Al–Mg gives higher weld metal ductility.

[5] For welding 1080A to itself, 1080A filler metal should be used.

33.5.3 Copper and copper alloys

Copper is produced in several grades, which vary in weldability according to the nature and quantity of the residual elements present. The material has a high thermal conductivity, and heat conduction away from the weld area may restrict the size of molten pool that can be obtained. Preheat is applied to counteract this, particularly with thicker material. Table 33.26 gives an indication of the preheat temperatures for copper and various copper alloys.

Welding is normally carried out using the gas shielded processes, and the choice of gas influences the thickness above which preheat is desirable as in Table 33.27. In general, the welding speed and penetration increase with change in shielding gas in the order Ar, He, N_2, and the level of preheat decreases with the same order of gases.

Manual metal arc welding of copper and its alloys is possible, but the gas-shielded processes are preferred. Manual metal arc welding is used mainly when other methods or suitable gas-shielded consumables are not available.

Filler wires for gas welding and gas shielded arc welding of copper and copper alloys are given in Tables 33.28 and 33.29.

Tough pitch copper, which contains residual oxygen, is available in several degrees of purity, and only the high conductivity grades of tough pitch copper should be used for welding. The inert gas-shielded processes are suitable using boron deoxidized copper filler (Table 33.29, C21) where electrical conductivity is important, or silicon–manganese deoxidized filler (Table 33.29, C7). Argon, helium, or mixtures of these gases should be used for shielding. Tough pitch copper may also be bronze welded with silicon bronze or aluminium bronze electrodes, or braze welded with filler to Table 33.28, C2 (silicon brass). The presence of arsenic does not affect weldability. Oxy-acetylene welding is not recommended, due to the risk of 'gassing'.

Phosphorus-deoxidized (PDO) copper may be welded by the oxy-acetylene, TIG or MIG processes. Argon, helium or nitrogen may be used for gas-shielded methods, either separately or mixed.

Table 33.26 SUGGESTED PREHEATING CONDITIONS FOR VARIOUS COPPER ALLOYS USING ARGON SHIELDING

	Preheating temperature, °C	
Material type	*Minimum*	*Maximum*
Copper	300*	530
Silicon bronze	20	65
Phosphor bronze	175	290
70/30 Cu/Ni	20	110
Aluminium bronze	20	150

* 350 °C required for TIG welding.
For further information *see* P. G. F. duPré, *Philips Welding Reporter*, 1972, **8**, 14–26.

Table 33.27 THICKNESS ABOVE WHICH PREHEAT MAY BE REQUIRED—COPPER AND COPPER ALLOYS

	Shielding gas		
Process	*Argon*	*Helium*	*Nitrogen*
TIG	3 mm	6 mm	9 mm
MIG	6 mm	9 mm	12 mm

See Table 33.26 for further information.

Table 33.28 FILLER WIRES FOR GAS WELDING COPPER AND COPPER ALLOYS (BS 1453:1972)

	Element wt %							
Type	Cu	Zn	Pb	Al	Fe	Ni	Mn	Si**
C1	99.85 min†		0.010 max		0.030 max	0.10 max		
C2	57.0–63.0	rem.	0.03 max	0.03 max				0.2–0.5
C2B	56.0–60.0	rem.	0.05 max	0.01 max	0.25–1.2	0.2–0.8	0.01–0.50	0.04–0.15
C2C	56.0–60.0	rem.	0.05 max	0.01 max	0.25–1.2		0.01–0.50	0.04–0.15
C3	59.0–61.0	rem.	0.03 max	0.03 max				
C4	57.0–63.0	rem.	0.03 max	0.03 max	0.1–0.5		0.05–0.25	0.15–0.3
C5	45.0–53.0	rem.	0.03 max	0.03 max.	0.5 max	8.0–11.0	0.5 max	0.15–0.5
C6	41.0–45.0	rem.	0.03 max	0.03 max	0.3 max	14.0–16.0	0.2 max	0.2–0.5

** For other elements see next page.

Table 33.28 FILLER WIRES FOR GAS WELDING COPPER AND COPPER ALLOYS (BS 1453:1972)—*continued*

Type	** *Element* wt %						*Total impurities excluding* Ag, Ni, As, P
	Sn	As	Sb	Bi	P	Tl	
C1	0.01 max	0.05 max	0.005 max	0.003 0 max	0.015–0.08	0.010 max*	0.060 max
C2	0.5 max						
C2B	0.8–1.1						0.50 max incl. Pb and Al
C2C	0.8–1.1						0.50 max incl. Pb and Al
C3							0.50 max
C4	0.5 max						
C5	0.5 max						
C6	1.0 max						

*Se plus Tl: 0.020% max. †Includes Ag 0.5–1.2%. ** For other elements *see* previous page.

The use of nitrogen produces a hotter arc with increased penetration, but with MIG welding, less satisfactory metal transfer may result. Phosphorus content is important, and should be as low as possible to minimize porosity. Phosphorus does not act as an efficient deoxidant in gas-shielded welding, and for this reason filler wires containing additional deoxidants should be used. Autogenous welding is not possible without the risk of porosity, and if welding without filler wire is required, zinc deoxidized (cap) copper can be employed, using the TIG process. Zinc content is relatively unimportant within the range 0.5–3.0% zinc. Oxy-acetylene welds are made using a copper–silver–phosphorus filler rod (Table 33.28, C1) and a flux. Such welds are hot hammered during welding to remove porosity and frequently cold hammered to improve mechanical properties.

Oxygen-free high conductivity copper may be oxy-acetylene welded without gassing, but if TIG or MIG welding is employed, there is a risk of porosity formation which may be overcome by using boron–copper filler wire.

All grades of copper may be bronze welded using the manual metal arc; TIG or MIG processes and fillers of the aluminium, silicon or tin bronze types. The technique involves the use of a wide edge preparation, preferably a fillet and the use of soft arcs to minimize penetration. Deoxidized and oxygen-free copper may also be braze welded using silicon brass (Table 33.28 C2) or manganese bronze (Table 33.28 C4) fillers.

COPPER–ALUMINIUM ALLOYS

Gas welding is not recommended but carbon arc welding using cryolite flux, manual metal arc welding, or preferably the argon or helium TIG welding processes may be used. The iron-bearing single phase alloy Cu/7 Al/3 Fe is normally welded with a nickel-bearing duplex alloy (Table 33.29, C20). Most duplex and complex bronzes are welded with fillers of matching composition, as are the manganese–aluminium bronzes. An important consideration is corrosion resistance, and care should be taken to avoid a combination of manganese–aluminium bronze and the normal single phase and duplex bronzes. The nickel-bearing filler C20 is resistant to dealuminification in all but the most severe environments and is frequently used as a facing deposit in welds in BS 1400: AB2C castings, which are normally made with 10% aluminium fillers (Table 33.29, C13). If a single phase deposit is required, C12 Fe filler may be used for a corrosion resistant layer on top of a more crack resistant filler. If stress corrosion is a problem, a small tin addition may be made to both parent and filler metals.

The welding of the aluminium bronzes should be carried out with as low a heat input as possible. Thus, preheating and high inter-run temperatures should be avoided, as should weaving when depositing filler metal. It is often necessary to give a post-weld thermal treatment to eliminate the risk of stress corrosion cracking.

COPPER–NICKEL ALLOYS

The problems of embrittlement and porosity in welding cupro-nickel may be overcome by using filler wires containing manganese as a desulphurizer and titanium as a deoxidant. Filler wires are

available for 90/10 and 70/30 cupro-nickels (C16 and C18, Table 33.29). Either argon arc or inert-gas metal arc welding is normally employed, but flux-coated manual metal arc electrodes are available for some alloys.

COPPER–SILICON ALLOYS

Silicon bronzes and 'Everdur' are readily weldable, the inert-gas processes being preferred. Parent metal filler is employed (C9, Table 33.29). Bronze welding is also possible.

COPPER–TIN ALLOYS

Tin bronzes usually contain phosphorus, and their welding behaviour is somewhat similar to phosphorus deoxidized copper, both oxy-acetylene and TIG welds tending to be porous. Filler rods employed are given in Table 33.29 (C10, C11). Bronze welding is preferable.

Table 33.29 FILLER RODS AND WIRES FOR THE GAS-SHIELDED WELDING OF COPPER AND COPPER ALLOYS (BS 2901: PART 3: 1983)

	Element wt %				
Type	Cu	Al	Ti	Fe	Ni
C7*	98.5 min	0.03 max		0.03 max	0.10 max
C8†	99.4 min	0.1–0.3 Al + Ti: 0.25–0.5	0.1–0.3	0.30 max	0.10 max
C9	Remainder	0.03 max		0.10 max	0.10 max
C10	93.8 min	0.03 max			
C11	92.3 min	0.03 max			
C12	90.0 min	6.0–7.5		(Fe + Ni + Mn)‡: 1.0–2.5	
C12Fe	89.0 min	6.5–8.5		2.3–3.5	
C13	86.0 min	9.0–11.0		0.75–1.5	1.0 max
C16	Remainder	0.03 max	0.20–0.50	1.5–1.8	10.0–12.0
C18	66.5 min	0.03 max	0.20–0.50	0.4–1.0	30.0–32.0
C20	80.5–85.0	8.0–9.5		1.5–3.5	3.5–5.0
C22	Remainder	7.0–8.5		2.0–4.0	1.5–3.0
C23	Remainder	6.0–6.4		0.5–0.7	0.1 max
C24	Remainder	0.01 max		0.10 max	
C25	Remainder	0.05 max	0.05 max	0.05 max	1.0–1.7
C26	Remainder	8.5–9.5		3.0–5.0	4.0–5.5

	Element wt %				
Type	Mn	Si	Zn	Sn	P
C7*	0.15–0.35	0.20–0.35		1.0 max	0.015 max
C8†					0.015 max
C9	0.75–1.25	2.75–3.25			0.020 max
C10			0.5 max	4.5–6.0	0.02–0.40
C11				6.0–7.5	0.02–0.40
C12		0.10	0.2 max		
C12Fe		0.10 max	0.2 max		
C13	1.0 max	0.10 max	0.2 max		0.01 max
C16	0.5–1.0	0.01 max			0.01 max
C18	0.5–1.5	0.01 max			
C20	0.5–2.0	0.10 max	0.2 max		
C22	11.0–14.0	0.10 max	0.15 max		
C23§	0.5 max	2.0–2.4	0.4 max	0.1 max	
C24	1.5–2.5		0.2 max		
C25	0.15–0.4	0.4–0.7		4.5–6.0	
C26	0.6–3.5	0.10 max	0.10 max		

* These rods and wires are intended for welding Cu using Ar or He as the shielding gas.
† These rods and wires are intended for welding Cu using N_2 as the shielding gas: Ar or He may be used.
‡ Optional elements.
§ 0.05%Mg max.

The weldability of the gunmetals depends upon the lead content. Those containing 0.1%Pb are weldable by the TIG, MIG, manual metal arc and gas welding processes. At 0.1–0.5%Pb, manual metal arc with phosphorus bronze electrodes or bronze welding offers a reasonable chance of success. The leaded gunmetals can be considered to be unweldable although single layer cosmetic repairs may sometimes be made successfully.

Both classes of material have long freezing ranges and are consequently hot short. They are also subject to coring and shrinkage porosity if large molten pools are employed.

COPPER–ZINC ALLOYS

The welding of brass is not easy, due to excessive fume formation, and fume extraction plant may prove necessary. Oxy-acetylene welding using an oxidizing flame and parent metal filler or silicon or manganese–brass or nickel–silver fillers is possible. TIG and MIG welding both employ zinc-free filler alloys in preference to brass, although brass fillers are available for the former process (Table 33.29). For manual metal arc and MIG welding, silicon bronze or aluminium bronze electrodes are employed. The susceptibility of brasses to season cracking should be borne in mind, and stress relief of brass components is desirable.

BERYLLIUM–COPPER

Alternating current TIG welding is preferred. In order to obtain the maximum joint efficiency, welding speed should be high, and post-weld heat treatment is essential. Both the high Be/low Co and high Co/low Be alloys should be welded in the solution heat-treated condition using high Be filler rods. Post-weld ageing will restore most of the strength and hardness. Although possible, consumable electrode methods are not recommended due to the toxicity problem.

CADMIUM–COPPER

Experience is limited, but it is suggested that for gas welding, filler rods to BS 1453 C1 (Table 33.28) should be used. Parent metal filler may be suitable for inert-gas welding. Cadmium is extremely toxic and fusion welding should be attempted only under stringent ventilation control.

CHROMIUM–COPPER

Chromium–copper is heat-treatable and suffers from a loss in mechanical properties in the heat affected zone. It also exhibits a tendency to hot shortness. Bronze welding with aluminium bronze filler has been successfully employed, but joint efficiencies are low after post-weld heat treatment. Joints of low restraint may be made using a d.c. electrode negative TIG technique with helium shielding. The components should be solution treated prior to welding, and subsequently aged.

OTHER COPPER-RICH ALLOYS

Silver–copper may be welded by the inert-gas processes using boron–copper filler wire. Tellurium– and selenium–copper suffer from excessive weld porosity. Leaded copper is hot short, and welding is difficult.

33.5.4 Lead and lead alloys

Lead and its alloys may be welded by the oxy-acetylene process using no flux and a neutral flame. Other fuel gases, such as hydrogen, butane or coal gas, may be used. The edges should be cleaned before welding, and parent metal filler is used. Other processes are little used.

33.5.5 Magnesium alloys

Magnesium alloys are preferably welded by the a.c. TIG process with argon shielding. Normal inert-gas metal arc welding is not suitable for magnesium because of the high deposition rates required. However, the pulsed version of this process has found application. The use of gas welding is confined to the wrought Mg–Mn and Mg–Al–Zn alloys, and should never be used for fillet or lap welds or for welds in zirconium-bearing alloys due to the corrosion hazard from flux residues. Proprietary fluxes are available. Flux removal and chemical cleaning should be followed by chromating.

The argon arc process may be used for welding all the commercially available alloys, with the exception of the wrought Mg–3%Zn–0.7%Zr and Mg–5.5%Zn–0.7%Zr alloys and the cast Mg–4.5%Zn–0.7%Zr alloy.

British Standard filler alloys are listed in Table 33.30. For castings parent metal filler is invariably used. A guide to filler metal selection is given in Table 33.31 for wrought and cast products to BS 3370, 3372, 3373 and 2970.

Table 33.30 FILLER RODS AND WIRES FOR GAS-SHIELDED WELDING OF MAGNESIUM ALLOYS (AFTER BS 2901:PART 4:1983)

	Element wt %					
Type	Al	Zn	Mn	Zr	Rare earths	Th
MAG 1	7.5–9.0	0.3–1.0	0.15–0.4			
MAG 3	9.0–10.5	0.3–1.0				
MAG 5		3.5–5.0		0.4–1.0	0.75–1.75	
MAG 6		0.8–3.0		0.4–1.0	2.5–4.0	
MAG 8		1.7–2.5	0.15 max	0.4–1.0	0.10 max	2.5–4.0
MAG 9		5.0–6.0	0.15 max	0.4–1.0	0.20 max	1.5–2.3
MAG 111	2.5–3.5	0.6–1.4	0.15–0.40			
MAG 141	0.02 max	0.75–1.5	0.15 max	0.4–0.8		

33.5.6 Nickel and nickel alloys

These materials fall into two groups, namely solid solution and precipitation hardening alloys. Nickel alloys are highly sensitive to contamination during welding and to the presence of various minor impurities. To avoid weld cracking and porosity, all surfaces to be welded and filler rods must be grease-free and scrupulously clean. The presence of sulphur, lead and zinc are particularly detrimental, the effects of sulphur being most marked with the chromium-free alloys. Most nickel alloy weld metals are quite fluid and, if possible, components should be welded in the flat position.

It is normally recommended that nickel alloys be stress-free prior to welding. The solid solution hardened grades should be annealed, although a certain amount of cold work is permissible. Post-weld heat treatment is not usually necessary. Incoloy DS* containing silicon is sensitive to hot cracking and restraint must be kept to a minimum. Precipitation hardened materials should be solution treated before welding, and aged afterwards. Some materials based on the Ni–Al–Ti precipitation hardening system are susceptible to post-weld heat treatment cracking, depending on the joint restraint, as are austenitic stainless steels. In such cases, a full heat treatment after welding is recommended. HAZ liquation cracking may arise and in certain precipitation hardened alloys, such as Nimonic* 80A, 90 and PK33, restricts the thickness that can be welded to below 5 mm.

TIG welding, both manual and mechanized is the most widely used process for sheet material. A.c. or d.c. may be employed, although the latter is preferred. Most alloys may be welded and suitable fillers are listed in Tables 33.32 and 33.33. Chromium-free grades are susceptible to porosity during autogenous welding, and the addition of filler is recommended so that at least 50% of the weld pool volume is constituted by filler metal. Commercial purity argon is generally used for shielding with additions of up to 10% hydrogen helping to reduce porosity and increase welding speeds. Helium or argon–helium mixtures are applicable and may also be advantageous in increasing welding speed. Nitrogen in the gas or from the atmosphere can cause porosity. Complete coverage of the weld area with shielding gas is essential. The largest gas nozzle possible should be used with the minimum practicable distance from the nozzle to the workpiece, while adequate gas backing must be applied. Many nickel alloys form tenacious oxide films, which tend to be patchy and interfere with weld uniformity. Argon–5% hydrogen mixtures can be used as backing and shielding gases to overcome such problems. Nickel–molybdenum alloys may give a very fluid weld pool, when the TIG process is preferred for positional welding, in view of the facility of control.

* Henry Wiggin & Co. Ltd

Table 33.31 *SELECTION OF FILLER ALLOYS FOR GAS-SHIELDED WELDING MATCHING AND DISSIMILAR MAGNESIUM ALLOYS (AFTER BS 3019: PART 1: 1984)*

Parent metal combination		Mg–5.5Zn–2Th–0.5Zr MAG 9	Mg–3Th–2Zn–0.5Zr MAG 8	Mg–2Zn–3RE–0.5Zr MAG 6	Mg–4Zn–1RE–0.5Zr MAG 5	Mg–10Al–0.5Zn–Mn MAG 3	Mg–8Al–0.5Zn–Mn MAG 1 MAG 2 or MAG 7	Mg–3Zn–0.5Zr MAG 151	Mg–6Al–1Zn–Mn MAG 121	Mg–3Al–1Zn–Mn MAG 111
Mg–3Al–1Zn–Mn	MAG 111	NR	NR	MAG 6 [P]	MAG 6 [P]	MAG 3	MAG 1	NR	MAG 1	MAG 111
Mg–6Al–1Zn–Mn	MAG 121	NR	NR	MAG 6 [P]	MAG 6	MAG 3	MAG 1	NR	MAG 1	
Mg–3Zn–0.5Zr	MAG 151	MAG 141 [P]	MAG 141 [P]	MAG 141 [P]	MAG 141 [P]	NR	NR	MAG 141 [P]		
Mg–1Al–0.5Zn–Mn	MAG 1 MAG 2 or MAG 7	MAG 8 [P]	MAG 8 [P]	MAG 6 [P]	MAG 6 [P]	MAG 3	MAG 1			
Mg–10Al–0.5Zn–Mn	MAG 3	MAG 8 [P]	MAG 8 [P]	MAG 6 [P]	MAG 6 [P]	MAG 3				
Mg–4Zn–1RE–0.5Zr	MAG 5	MAG 8 [P]	MAG 8 [P]	MAG 6	MAG 5					
Mg–2Zn–3RE–0.5Zr	MAG 6	MAG 8 [P]	MAG 8 [P]	MAG 6						
Mg–3Th–2Zn–0.5Zr	MAG 8	MAG 8	MAG 8							
Mg–5.5Zn–2Th–0.5Zr	MAG 9	MAG 9								

Key: NR = not recommended, P = sensitive to cracking.

For welding nickel and its alloys in heavier gauges, manual metal arc and MIG welding are generally suitable, the welding technique differing little from that practised with austenitic stainless steels. With manual metal arc welding, it is advisable to use small gauge electrodes, and to allow cooling between weld runs. Complete slag removal is imperative, particularly for high temperature service where reactions between the metal and residual slag may cause severe corrosion. Table 33.33 gives typical consumables for some of the more common commercial alloys: d.c. current is essential with positive electrodes. There is no British Standard for manual metal arc electrodes for nickel alloys, but a number of proprietary makes are obtainable.

Argon shielding is preferred with MIG welding, although the addition of up to 20% helium may be of benefit in spreading the weld pool and reducing the incidence of cold laps. Spray, globular dip, or dip transfer conditions have been employed for most nickel alloys, with consumables shown in Tables 33.32 and 33.33. Spray transfer gives the highest deposition rates but may cause weld metal cracking, particularly if the welding conditions are such that a weld bead with a concave surface is produced. Pulsed MIG welding has also been found applicable for nickel alloys, especially for positional welding.

Oxy-acetylene welding is little used for nickel alloys. It is suitable for most solid solution hardened alloys and Monel K-500, although carbon pick-up may reduce corrosion resistance. Nickel and Incoloy DS can be welded without flux while fluxes are available for the Monel, Incoloy, Inconel, Brightray and Hastelloy D alloys. Fluxes used with the chromium-containing alloys must be free from boron, since the presence of boron compounds can cause weld metal cracking. Complete flux removal after welding is essential. The flame should be slightly reducing for nickel and Monel 400, more reducing with the chromium-containing alloys, and highly reducing for Monel K-500 and Hastelloy D. Filler alloys are given in Table 33.33.

Table 33.32 FILLER RODS AND WIRES FOR GAS SHIELDED WELDING OF NICKEL ALLOYS (BS 2901:PART 5:1983)

	Element wt %						
Type	Ni	Cr	Co	Fe	Mo	Ti	Al
NA32	93.0 min			1.0 max		2.0–3.50	1.50 max
NA33	62.0–69.0			2.5 max		1.5–3.0	1.25 max
NA34	Remainder	18.0–21.0		0.5 max			
NA35	67.0 min	18.0–22.0	0.12 max	3.0 max		0.75 max	
NA36	Remainder	18.0–21.0	15.0–21.0	3.0 max		1.8–3.0	0.9–2.0
NA37	Remainder	16.0–20.0	12.0–16.0	1.0 max	5.0–9.0	1.5–3.0	1.7–2.5
NA38	Remainder	19.0–21.0	19.0–21.0	0.7 max	5.6–6.1	1.9–2.4	0.3–0.60
NA39	67.0 min	14.0–17.0		0.80 max		2.5–5.0	
NA40	Remainder	20.5–23.0	0.5–2.5	17.0–20.0	8.0–10.0		
NA41	33.0–46.0	19.5–23.5	1.0 max	Remainder	2.5–3.40	0.6–2.20	0.20 max
NA42	42.0–45.0	15.0–18.0	2.0 max	Remainder	2.5–4.0	0.9–1.5	0.9–1.5
NA43	58.0 min	20.0–23.0	1.0 max	5.0 max	8.0–10.0	0.40 max	0.40 max
NA44	Remainder	1.0 max	1.0 max	2.0 max	26.0–30.0		
NA45	Remainder	14.0–18.0	2.0 max	3.0 max	14.0–17.0	0.70 max	

	Element wt %				
Type	Mn	C	Si	Cu	*Notes*
NA32	1.00 max	0.15 max	0.75 max	0.25 max	Other elements 0.5% max
NA33	3.0–4.0	0.15 max	1.25 max	Remainder	
NA34	1.2 max	0.26 max	0.50 max	0.20 max	
NA35	2.5–3.50	0.10 max	0.50 max	0.50 max	Ta 0.30% max: (Nb + Ta) 2.0–3.00%
NA36	1.0 max	0.13 max	1.5 max	0.2 max	
NA37	0.5 max	0.07 max	0.5 max	0.2 max	B 0.005% max: Zr 0.06% max
NA38	0.2–0.60	0.04–0.08	0.1–0.40	0.2 max	(Ti + Al) 2.4–2.8%
NA39	2.0–2.75	0.08 max	0.35 max	0.50 max	
NA40	1.0 max	0.15 max	1.0 max	0.50 max	W 0.2–1.0%
NA41	1.0 max	0.05 max	0.50 max	1.5–3.00	Other elements 0.5% max
NA42	0.2 max	0.10 max	0.3 max	0.5 max	B 0.005% max: Zr 0.05% max
NA43	0.5 max	0.10 max	0.50 max	0.50 max	(Nb + Ta) 3.15–4.15%
NA44	1.0 max	0.02 max	0.50 max	0.50 max	
NA45	1.0 max	0.015 max	0.50 max	0.50 max	

Table 33.33 TYPICAL CONSUMABLES FOR WELDING NICKEL ALLOYS

	Welding process		
Parent material	*Manual metal arc*	*Gas*	*Inert gas shielded*
Nickel	Nickel electrode 141	Nickel 41	NA32 (Nickel 61)
Monel† 400	Monel electrode 190	Monel 40	NA33 (Monel 60)
Monel K-500	Monel electrode 134	Monel 64	Monel 64
Inconel† 600	Inconel electrodes 132 or 182	NA34 (NC80/20)†	NA35 (Inconel 82)
Incoloy† 800	Incoweld† A	NA34 (NC80/20)	NA35 (Inconel 82)
Incoloy DS	Incoweld A	NA34 (NC80/20)	NA34 (NC80/20)
Nimonic†	Inconel electrodes 132 or 182	NA34 (NC80/20)	NA34 (NC80/20)
Nimonic 80A			NA36 (Nimonic 90)
Nimonic 90			NA36 (Nimonic 90)
Hastelloy* X			NA40

See Table 33.32 for NA32, 33, 34, 35, 36 and 40.
* Union Carbide U.K. Ltd.
† Henry Wiggin & Co. Ltd.

Submerged-arc welding is applicable to various nickel alloys, generally when heavy section material is being joined for corrosion resistant applications. Only a limited range of flux types is available. D.c. is used, with electrode positive being preferred to obtain deeper penetration and reduced risk of slag entrapment.

Electron beam welding can be used for most nickel alloys, and is a common fabrication process for high temperature items such as gas turbine components.

33.5.7 Noble metals

SILVER

Silver is difficult to weld due to its property of oxygen absorption. A slightly reducing flame is used for oxy-acetylene welding with a borax–boric acid flux. Silver–0.5% aluminium rods reduce the tendency to porosity formation. Argon arc welding using d.c. is possible, though slight porosity is usually present. A.c. argon arc welding using aluminium bearing fillers or traces of aluminium powder in the joint preparation is also possible.

GOLD

Gold and gold–copper alloys are readily welded by the gas welding process using parent metal filler and borax fluxes. A reducing flame is recommended for the alloys.

PLATINUM

An oxidizing oxy-hydrogen flame is used without flux. The platinum–rhodium and platinum–iridium alloys may also be welded using this technique.

33.5.8 Refractory metals

The problem common to the welding of this group of materials is their strong affinity for atmospheric and other gases, and the consequent need to avoid contamination, both of the molten pool and the surfaces of the cooling solidified weld bead and heat affected zones. For arc welding this problem is overcome in two ways, either by provision of a complete argon-filled chamber in which the workpiece and welding head is placed, or by the provision of extended argon shrouds and argon backing.

These materials may all be welded by the tungsten inert gas arc process, and titanium has been successfully welded by the inert-gas metal arc process. The use of this process may eventually be extended to cover other materials in this group. Electron beam welding is also generally applicable, while, given appropriate gas shielding, laser welding may be suitable in some cases. Solid state joining by friction welding of diffusion bonding is summarized in Tables 33.4 and 33.5.

TITANIUM AND TITANIUM ALLOYS

The α titanium alloys (e.g. commercially pure Ti, Ti–5%Al–2½%Sn) are fully weldable, as are alloys with only small amounts of eutectoid formers or β stabilizers (e.g. Ti–2½% Cu, Ti–8%Al–1%Mo–1%V, Ti–7%Al–2%Nb–1%Ta). As the β stabiliser content rises, the weld zone becomes less ductile and eventually brittle. The Ti–6%Al–4%V alloy represents about the limiting composition for αβ alloys for good weldability.

In the weldable alloys, TIG welds (d.c., electrode negative) may be made without filler or with parent metal filler depending on thickness. For αβ alloys, the ductility of the weld metal can be increased by using commercially pure Ti filler, but this will not improve the ductility of the heat affected zone. MIG welding is feasible, but experience is limited. All metal reaching higher than 600–650 °C should be protected by argon.

NIOBIUM AND TANTALUM AND THEIR ALLOYS

The same technique as for titanium should be used, except that argon protection will be required at and above 400 °C.

MOLYBDENUM

Electron beam and TIG (d.c., electrode negative) welds can be made, but the weld zone will be brittle below 300–500 °C. The techniques used for titanium should be applied. The metal produced by sintering gives grossly porous welds, and that made by arc casting should be used.

ZIRCONIUM ALLOYS

Experience is limited to the zirconium–tin and zirconium–niobium alloys, which are used in nuclear engineering. These materials are particularly susceptible to nitrogen contamination, which is harmful to the corrosion resistance. Superficial contamination during welding is removed by pickling. D.c. electrode negative is used, and gas cover should extend to areas in excess of 400 °C.

URANIUM

Uranium may be welded without difficulty by the TIG process using d.c. electrode negative. It is less sensitive to contamination than titanium.

33.5.9 Zinc and zinc alloys

Zinc and zinc-base castings are difficult to weld. The oxy-acetylene process using a slightly reducing flame and a zinc-ammonium chloride flux is most suitable. Parent metal filler should be used.

33.5.10 Dissimilar metals

Direct fusion welding of dissimilar metals is possible in certain cases, and special techniques have been developed for difficult combinations.

Steels may be joined to nickel alloys, but the joint dilution and selection of filler materials must be made to give either a high nickel–alloy weld or a weld composition falling within the shaded area of the Schaeffler diagram (Figure 33.3).

Combinations of copper and chromium should be avoided, as when welding Monel to chromium bearing steels, and in such cases, nickel-base filler should be interposed.

Steels may be joined to copper and copper alloys by bronze welding techniques, but joining to aluminium involves precoating of the steel with aluminium–silicon brazing alloy, and joint ductility is low.

Copper may be welded direct to nickel, provided a deoxidant (titanium) is present either in the nickel or the filler wire.

Copper to aluminium joints are made by coating the copper with a layer of silver solder (BS 1845: Type AG1 or AG2) and welding by argon arc or inert gas metal arc processes, using aluminium 10% silicon filler.

33.6 British standards relating to welding

General

BS	
499: —	Welding terms and symbols. Part 1: 1983 Welding, brazing and thermal cutting glossary. Part 2: 1980 Specifications for symbols for welding.
499C: 1980	Chart of British Standard welding symbols (based on BS 499: Part 2).
679: 1977	Filters for use during welding and similar industrial operations.
1542: 1982	Equipment for eye, face and neck protection against non-ionizing radiation arising during welding and similar operations.
2653: 1955	Protective clothing for welders.
5378: —	Safety signs and colours. Part 1: 1980 Colour and design. Part 2: 1980 Colorimetric and photometric properties of materials.

Processes

1140: 1980	Specification for resistance spot welding of uncoated and coated low carbon steel.
1723:	Brazing. Part 1: 1986 Specification for brazing. Part 2: 1986 Guide to brazing.
1724: 1959	Bronze welding by gas.
1821: 1982	Class I oxy-acetylene welding of ferritic steel pipework for carrying fluids.
2630: 1982	Specification for resistance projection welding of uncoated low carbon steel sheet and strip using embossed projections.
2633: 1987	Class I arc welding of ferritic steel pipework for carrying fluids.
2640: 1982	Class II oxy-acetylene welding of carbon steel pipework for carrying fluids.
2971: 1977	Class II arc welding of carbon steel pipework for carrying fluids.
2996: 1958	Projection welding of low carbon wrought steel studs, bosses, bolts, nuts and annular rings.
3019: —	General recommendations for manual inert-gas tungsten-arc welding. Part 1: 1984 Specification for TIG welding of aluminium, magnesium and their alloys. Part 2: 1960 Austenitic stainless and heat resisting steels.
3571: —	General recommendations for manual inert-gas metal-arc welding. Part 1: 1985 Aluminium and aluminium alloys.

Processes—*continued*

BS	
4204: 1981	General requirements for the flash welding of steel pipes and tubes for pressure and other high duty applications.
4515: 1984	Field welding of carbon steel pipelines on land and offshore.
4570: 1985	Fusion welding of steel casting.
4677: 1984	Arc welding of austenitic stainless steel pipework for carrying fluids.
5135: 1984	Arc welding of carbon and carbon–manganese steels.
6223: 1982	Friction welding of butt joints in metals for high duty applications.
6265: 1982	Resistance seam welding of uncoated and coated low carbon steel.
6512: 1984	Repair of surface discontinuities of hot-rolled steel plates and wide flats.
6944: 1988	Flash welding of butt joints in ferrous metals (excluding pressure piping applications).

Equipment

638: —	Arc welding power sources, equipment and accessories. Part 1: 1979 Specification for oil-cooled power sources for manual, semi-automatic and automatic metal-arc welding and for TIG welding. Part 2: 1979 Specification for air-cooled power sources for manual metal-arc welding with covered electrodes and for TIG welding. Part 3: 1979 Specification for air-cooled power sources for semi-automatic and automatic metal-arc welding. Part 4: 1979 Specification for welding cables. Part 5: 1988 Specification for accessories. Part 8: 1984 Specification for electrode holders and hand held torches and guns for MIG, MAG and TIG welding.
1389: 1986	Dimensions of hose connections for welding and cutting equipment.
3065: 1982	The rating of resistance welding and resistance heating machines.
3856: 1986	Platens for projection welding machines.
4215: 1987	Spot welding electrodes and electrode holders and ancillary equipment.
4577: 1970	Materials for resistance welding electrodes and ancillary equipment.
4819: 1972	Resistance welding water-cooled transformers of the press-package and portable types.

Equipment—*continued*

BS	
5120:1987	Rubber hose for gas welding and allied processes.
5741:1979	Specification for pressure regulators used in welding, cutting and related processes.
6678:1986	Tungsten electrodes for inert gas shielded arc welding and for plasma cutting and welding.

Filler rods and electrodes

639:1986	Covered electrodes for the manual metal-arc welding of carbon and carbon-manganese steels.
807:1955	Spot welding electrodes.
1453:1972	Filler rods and wires for gas welding.
1845:1984	Filler metals for brazing.
2493:1985	Low alloy steel electrodes for manual metal-arc welding.
2901:1983	Filler rods and wires for gas-shielded arc welding. Part 1 Ferritic steels Part 2 Austenitic stainless steels. Part 3 Copper and copper alloys. Part 4 Aluminium and aluminium alloys and mangesium alloys. Part 5 Nickel and nickel alloys.
2926:1984	Chromium-nickel austenitic and chromium steel electrodes for manual metal-arc welding.
3067:1984	Dimensions of blanks for seam welding wheels.
4165:1984	Electrode wires and fluxes for the submerged arc welding of carbon steel and medium tensile steel.
5465:1987	Electrodes wires and fluxes for the submerged arc welding of austenitic stainless steel based on weld metal composition.

Testing and inspection

709:1983	Methods of testing fusion welded joints and weld metal in steel.
1295:1987	Training of welders.
2600: —	Methods of radiographic examination of fusion-welded butt joints in steels. Part 1:1983 5 mm up to and including 50 mm thick. Part 2:1973 Over 50 mm up to and including 200 mm thick.
2704:1978	Calibration blocks and recommendations for their use in ultrasonic flaw detection.
2910:1986	Methods for radiographic examination of fusion-welded circumferential butt joints in steel pipes.
3451:1973	Methods of testing fusion welds in aluminium and aluminium alloys.
3923: —	Methods for ultrasonic examination of welds. Part 1:1986 Manual examination of fusion butt joints in ferritic steels.

Testing and inspection—*continued*

BS	
	Part 2:1972 Automatic examination of welded seams. Part 3:1972 Manual examination of nozzle welds.
3971:1980	Image quality indicators for radiography and recommendations for their use.
4069:1982	Magnetic flaw detection inks and powders.
4129:1967	Resistance welding properties of welding primers and weld-through sealers.
4206:1967	Methods of testing fusion welds in copper and copper alloys.
4416:1969	Method for penetrant testing of welded or brazed joints in metals.
4778:1979	Glossary of general terms used in quality assurance (including reliability and maintainability terms).
4870: —	Approval testing of welding procedures. Part 1:1981 Fusion welding of steel. Part 2:1982 TIG or MIG welding of aluminium and its alloys. Part 3:1985 Arc welding of tube to tube-plate joints in metallic materials. Part 4:1988 Automatic fusion welding of metallic materials, including welding operator approval.
4871: —	Approval testing of welders working to approved welding procedures. Part 1:1982 Fusion welding of steel. Part 2:1982 TIG or MIG welding of aluminium and its alloys. Part 3:1985 Arc welding of tube to tube-plate joints in metallic materials.
4872: —	Approval testing of welders when welding procedure approval is not required. Part 1:1982 Fusion welding of steel. Part 2:1976 TIG or MIG welding of aluminium and its alloys.
5289:1976	Code of practice for visual inspection of fusion-welded joints.
5430: —	Periodic inspection, testing and maintenance of transportable gas containers (excluding dissolved acetylene containers). Part 2:1977 Welded steel containers of water capacity 1 l up to 130 l.
6693: —	Diffusible hydrogen. Part 1:1986 Method for determination of hydrogen in MMA weld metal using 3 day collection. Part 2:1986 Method for determination of hydrogen in MMA weld metal. Part 3:1988 Primary method for the determination of diffusible hydrogen in manual metal arc ferritic steel weld metal. Part 4:1988 Primary method for the determination of diffusible hydrogen in submerged arc ferritic steel weld metal. Part 5:1988 Primary method for the determination of diffusible hydrogen in MIG, MAG, TIG or cored electrode ferritic steel weld metal.
6787:1987	Method for determination of ferrite

Materials—*continued*

BS

	number in austenitic weld metal deposited by covered chromium–nickel steel electrodes (ISO 8249:1985).
7009:1988	Guide to the application of real-time radiography to weld inspection.

PD

6493:1980	Guidance on some methods for the derivation of acceptance levels for defects in fusion-welded joints.

Materials

1640: —	Steel butt-welding pipe fittings for the petroleum industry. Part 1:1962 Wrought carbon and ferritic alloy steel fittings. Part 2:1962 Wrought and cast austenitic Cr–Ni steel fittings. Part 3:1968 Wrought carbon and ferritic alloy steel fittings. Metric units. Part 4:1968 Wrought and cast austenitic Cr–Ni steel fittings. Metric units.
1965: —	Butt-welding pipe fittings for pressure purposes. Part 1:1963 Carbon steel.
3014:1958	'As welded' and cold drawn welded austenitic stainless steel tubes for mechanical, structural and general engineering purposes.
3600:1976	Dimensions and masses per unit length of welded and seamless steel pipes and tubes for pressure purposes.
3602: —	Steel pipes and tubes for pressure purposes: carbon and carbon manganese steel with specified elevated temperature properties. Part 1:1987 Seamless, electric resistance welded and induction welded tubes. Part 2:1978 Submerged arc-welded tubes.

Materials—*continued*

BS

3605:1973	Seamless and welded austenitic stainless steel pipes and tubes for pressure purposes.
3799:1974	Steel pipe fittings, screwed and socket welding for the petroleum industry.
4360:1986	Specification for weldable structural steels.
4534:1969	Weldable chromium–nickel cast steel tubes.
6323:1982	Seamless and welded steel tubes for automobile, mechanical and general engineering purposes.

Applications

855:1976	Welded steel boilers for central heating and hot water supply (rated output 44 kW to 3 MW).
2594:1975	Carbon steel welded horizontal cylindrical storage tanks.
2654:1984	Vertical steel-welded storage tanks with butt-welded shells for the petroleum industry.
2790:1986	Shell boilers of welded construction (other than water-tube boilers).
3256:1960	Small fusion-welded air reservoirs for road and railway vehicles.
4741:1971	Vertical cylindrical welded steel storage tanks for low-temperature service. Single wall tanks for temperatures down to −50°C.
5169:1975	Fusion-welded steel air receivers.
5387:1976	Specification for vertical cylindrical welded storage tanks for low-temperature service: double-wall tanks for temperatures down to −196°C.
5400: —	Steel, concrete and composite bridges. Part 6:1980 Specification for materials and workmanship, steel. Part 10:1980 Code of practice for fatigue.
5500:1988	Unfired fusion-welded pressure vessels.

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34 Soldering and brazing

34.1 Introduction

Soldering and brazing are useful, fairly simple joining processes in which metals are wetted and joined together by a dissimilar metal of lower melting temperature. When compared with adhesives, the join is permanent unless remelted, has good electrical and thermal conductivity and is unaffected by organic solvents. It is also resistant to failures at temperatures under those of the original joining technique. There are many filler metals available for a variety of applications with melting temperatures from just above room temperature upwards, the majority of conventional solders being molten below 300°C. Brazing is basically similar to soldering but takes place at a higher temperature, above 450°C according to the definitions of BS 499 but, unlike welding, always below the melting temperature of the parent metals. Brazing is also distinguished from welding by the fact that the brazed joint is formed mainly by capillary action between adjacent surfaces whereas welding starts by local melting of the base metals and continues with the addition of larger fillets of welding filler metal.

The majority of soldering and brazing alloys are based on binary or ternary eutectic systems, sometimes with small amounts of other addition elements. The compositions are chosen to have good wetting and capillarity at the joining temperatures, good corrosion resistance and reasonable strength. Brazed joints are generally significantly stronger than soldered ones and are usually intended to be permanent. The higher the joining temperature, the greater will be the heat-affected zone in the parent metals, with consequential possibilities of loss of temper due to annealing effects.

For joining to be successful the metal surfaces must be clean initially and are normally protected from oxidation during heating by the presence of a suitable flux. The wetting of a parent metal by a filler creates a metallurgical bond, the depth of which is diffusion controlled with the usual time- and temperature-dependent relationships. Overheating a joint, or repeated remaking of a joint usually has a deleterious effect on properties due to the formation of brittle intermetallic compounds.

Tin is present in most common soft solders and rapidly forms intermetallics with most base metals during soldering processes. These intermetallics may then continue to grow by solid-state reactions during storage and operational life of a joint. Under some time- and temperature-controlled conditions the tin can be totally converted to an intermetallic compound. The higher-temperature brazing operations form much deeper reaction zones of modified composition. Properly chosen brazing alloys will not form brittle intermetallics but the modified composition and microstructure will elevate the melting temperature, possibly to a value as high as the parent metal which will preclude the possibility of reworking joints.

34.2 Quality assurance

While soldering and brazing techniques have been employed satisfactorily for many years by skilled and semi-skilled personnel, modern manufacturing and quality control systems frequently require that process instructions are fully documented and refer to standards where relevant. Typical organizations preparing product standards covering the fluxes and filler metals include British Standards Institute, American Society for Testing and Materials (ASTM) and Deutsches Normenausschuss (DIN) but there are many others, some specifically aimed at particular industries or defence applications. European (CEN) standards are in preparation and will eventually replace individual European national standards. The following table covers some British Standards related mainly to general purposes.

Table 34.1 COMMON BRITISH STANDARDS FOR SOLDERING AND BRAZING

BS number	
219	Soft solders. Published 1977, confirmed 1984 and amended (AMD 5663:1987) to include lead-free solders for capillary joints in plumbing applications where the lead content of the solder is restricted—*see* BS 864:Part 2.
441	1980. Purchasing requirements for flux-cored and soft solder wire.
499	Welding terms and symbols, Part 1:1983. Glossary for welding, brazing and thermal cutting.
864	Capillary and compression tube fittings of copper and copper alloy, Part 2 Specification for capillary and compression fittings for copper tubes (AMD 5651:1987 covers the requirement for lead-free solders for potable water applications).
1723	Brazing. Part 1:1986 Specification for brazing. Part 2:1986 Guide to brazing. Part 3:1988 Methods for non-destructive and destructive testing. Part 4:1988 Methods for specifying brazing procedure and operator approval testing.
1724	Bronze welding by gas. 1959.
1845	Filler metals for brazing. 1984.
3252	Specification for ingot tin. 1986.
5245	Phosphoric acid based flux for soft soldered joints in stainless steel. 1975.
5625	Purchasing requirements and methods of test for fluxes for soft soldering (1980 edition at present under revision).
6811	Winding wires, Part 3 Specifications for particular types of winding wires, Section 3.1 1987. Polyurethane base enamel with solderable properties, Class 130 (for solder test refer to Section 2.4).

The requirements included in these specifications are typical of those needed for initiating a full quality control specification. For specific industries there are many other documents published both by national standards institutions and by organizations such as The European Space Agency and NASA. For military requirements for processing, cleanliness, protection and packaging there are other defence standards such as the American MIL and QQ series of specifications.

34.3 Soldering

Soldering is commonly used for structural applications, for the assembly of pipes and fittings for gas, water or other liquid services and is vital for electrical connections, especially on printed circuit boards. The relatively low melting temperatures of solders are beneficial in having little effect on the properties of the parent metals and adjacent items.

34.3.1 General considerations

Since the solder is weaker than the parts being fastened, the design of the joint must allow for this fact. Significant overlapping areas should be allowed and tensile and peeling forces should be avoided, leaving only sheer stresses at most on the solder which is mainly intended to act as filler and seal. Clearances of 0.07 to 0.25 mm are permissible between overlapping parts with approximately 0.1 mm being optimum for capillarity and joint strength. During soldering and solidification there should be no relative movement between joint faces and the use of jigs, self-locating designs or temporary solder-tagging is therefore recommended. The jigs and fixtures should not, however, act as local heat sinks that prevent efficient soldering.

Soldering itself should be carried out as quickly as possible in order to avoid the effects of overheating. The choice of heating method may be either direct, which is fast, or indirect, which reduces surface oxidation effects. For all joints it is essential to start with the components clean and for most it is also essential to protect surfaces from oxidation during soldering with a suitable flux.

34.3.2 Choice of flux

Fluxes have several purposes. They conduct heat to the component, modify or remove surface oxides and other contaminants and eliminate air from the solder wetting front.

The earliest and most active of fluxes are those water-based solutions such as the original 'killed spirits', zinc dissolved in hydrochloric acid, latterly with additions of ammonia and perhaps alcohol and/or a detergent. While very effective on the common metals such as steel, tinplate, copper and brass they are also very corrosive if not washed off thoroughly immediately soldering is completed. Aqueous solutions of orthophosphoric acid are also used for some applications, especially for the low melting point solders and for special steels. Subsequently organic-based fluxes have been developed, now forming four main groups, rosin, synthetic, synthetic resin and water-based organic fluxes.

Dependent on the application and the extent to which subsequent corrosion must be avoided, rosins may be mildly activated, with a halide content of less than 0.2%, activated with 0.2–0.5% halide or super-activated with even higher halide levels. Synthetic activated fluxes are based on formulations giving good wetting and excellent residue removal properties when cleaned with CFCs or other suitable solvents. Synthetic resin fluxes are now made with a low solids content which minimizes the need for cleaning and the latest water-soluble organic fluxes combine the best of soldering results with ease of washing clean. For critical assemblies such as wave-soldered printed circuit boards, it is essential to take expert opinion from manufacturers or other specialists in order to assure reproducible success.

The choice of flux is influenced by many factors including type and mass of metal to be soldered, cleanliness, heating techniques, type of solder and after-cleaning requirements. For example, the use of torch soldering techniques will require the use of a more active flux to deal with the extra tarnish caused by the flame.

The notes in Table 34.2 cover the common, and some of the less common, commercial metals (arranged in order of electrochemical potential, *see* Table 34.3).

Table 34.2 RECOMMENDED SOLDER FLUXES FOR ENGINEERING MATERIALS

Group No.	*Category*	*Flux type and possible protective finish with precautions*
1	Gold, solid or plated; gold–platinum alloys; wrought platinum	Both gold and platinum have excellent solderability. Soldering to gold and its alloys should be avoided because gold–tin intermetallics embrittle joints. Gold platings can be removed by solder-dipping to dissolve the gold followed by pre-tinning in a second, uncontaminated, solder pot. Rosin, non-activated flux is adequate. If gold cannot be removed, use indium–lead solder. Bright, hard gold platings may be difficult to wet due to the presence of certain alloying elements or organic additives derived from plating solutions: activated rosin flux is then required.
2	Rhodium	Not easy—inorganic flux.
3	Silver, solid or plated on copper; high silver alloys	Easily soldered with mildly activated flux or, when free of surface sulphide, non-activated rosin is preferable. If chloride-contaminated (from plating bath), may need abrasion. Use silver-loaded solder when joining to thin silver plate. The silver-saturated liquid reduces danger of scavenging. Silver-plated parts are not recommended for electrical circuits due to problem of silver migration and subsequent short circuits.
4(a)	Nickel, solid or plated; Monel	Difficult to solder. Use inorganic or organic acid for pre-tinning with solder and non-activated rosin after pre-tinning.
4(b)	Titanium	Impossible to solder without prior copper plating.
5(a)	Copper, solid or plated, tin-bronzes, gunmetals	With red oxide tarnish, can be soldered with mildly activated rosin. Black oxide only removable with activated rosin, organic acids or zinc ammonium chloride solutions (e.g. for radiator plates).
5(b)	Copper–nickel alloys	Not difficult to solder if clean and well fluxed but soldering is not commonly suitable for the service conditions for which these alloys are specified.

Table 34.2 RECOMMENDED SOLDER FLUXES FOR ENGINEERING MATERIALS—*continued*

Group No.	*Category*	*Flux type and possible protective finish with precautions*
5(c)	Nichrome alloys, austenitic, high corrosion-resistant steels; Nilo-K, Kovar, Monel, etc.	Very difficult to solder with inorganic acid fluxes, zinc chloride and ammonium chloride solutions. Some proprietary brands are available. Can be nickel-plated, but deposit must be non-porous or substrate will become oxidized by plating salts. All ionic matter, including handling contamination, must be thoroughly and immediately removed because this group is susceptible to stress corrosion cracking.
5(d)	Copper–aluminium alloys (aluminium bronzes)	Due to the tenacious alumina film which forms so rapidly, these alloys can only be soldered after copper plating or with techniques used for aluminium alloys.
6	Gilding metals (CuZn10 and CuZn20)	If clean, quite easy to solder with mildly activated resin. May be copper or silver-plated, but ensure good plating adhesion.
7	Commercial brasses (CuZn30 and CuZn40)	Use activated rosin if tarnish is thin. Impossible to solder—even with inorganic flux—if significant oxidation is visible, due to surface film of zinc oxide. Barrier plating of more than 3 μm nickel or copper is recommended for preserving solderability during shelf-life (should prevent zinc diffusion to surface). Barrier of 5 μm necessary if brass is leaded free-machining grade.
8	18% chromium-type stainless steel	*See* Group 5(b).
9	Tin-plated metals	New coatings are easily soldered with non-activated rosin flux. Activation of rosin depends on extent of tin oxide. Fused tin is preferred as it is less porous. Pure tin coatings not recommended for electronic applications due to risk of whisker growth. Should exceed 1 μm thickness as otherwise will react with copper and completely convert to intermetallic, which is extremely difficult to solder.
10	Tin–lead coatings, solid, plated or fused	Most suitable finish for easy soldering with non-activated rosin flux. Porous platings need activated flux. Should exceed 1 μm thickness, but lead slows down intermetallic formation. Good shelf-life for fused coatings on copper wire and printed circuits.
11	Lead, solid or plated; high lead alloys	Mildly activated flux required to penetrate surface oxides. High dissolution of lead in tin–lead solder produces joints with extremely low shear strength.
12	Aluminium–copper alloys (e.g. Duralumin and most of AA 2xxx series)	Impossible with tin–lead alloys. Generally, welding or dip-brazing are more suitable. Plate with zincate and copper. The low melting solders are preferred to avoid thermal stressing platings.
13	Iron, wrought, grey or Armco; plain carbon and low alloy steels	Solderability depends on oxide thickness. Clean, pickled surfaces can be easily soldered with mild or activated rosin flux. Passivated or phosphated steels require special fluxes.
14	Aluminium and most alloys other than in Group 12 (e.g. AA 1xxx, 3xxx and 5xxx series)	Can be soldered, but with special alloys (e.g. tin–zinc or cadmium–zinc alloys). May be friction-soldered without flux or, when aluminium oxide is removed, by ultra-sound. Some proprietary fluxes are available. Corrosion in aluminium-soldered joints is particularly troublesome; a water-proof coating is essential.
15(a)	Cast aluminium alloys other than aluminium–silicon alloys	As for Group 14 but choice of solder and flux requires specialist advice.
15(b)	Cadmium plating	Easy to solder with mildly or fully activated rosin fluxes. If passivated by chromate film, they are very difficult and require ammonium chloride-type flux. Fumes are toxic.
16	Hot dipped zinc plate	As for Group 15(b).
17	Zinc, wrought; zinc-based casting alloys; zinc plating	Generally, very difficult to solder due to oxidation. Use inorganic acid or special proprietary flux. Water-tight protection necessary to avoid corrosion.
18	Magnesium and magnesium-based alloys, cast or wrought	Not recommended because of poor strength and corrosion.

Table 34.3 ELECTROCHEMICAL POTENTIAL OF COMMON ENGINEERING MATERIALS

Group No.	*Category*	*Electrochemical potential V**
1	Gold, solid or plated; gold–platinum alloys; wrought platinum	+0.15
2	Rhodium	+0.05
3	Silver, solid or plated on copper; high silver alloys	0
4(a)	Nickel, solid or plated; Monel	−0.15
4(b)	Titanium	−0.15
5(a)	Copper, solid or plated, tin–bronzes, gunmetals	−0.20
5(b)	Copper–nickel alloys	−0.20
5(c)	Nichrome alloys, austenitic, high corrosion-resistant steels; Nilo-K, Kovar, Monel, etc.	−0.20
5(d)	Copper–aluminium alloys (aluminium bronzes)	−0.20
6	Gilding metals (CuZn10 and CuZn20)	−0.25
7	Commercial brasses (CuZn30 and CuZn40)	−0.30
8	18% chromium-type stainless steel	−0.35
9	Tin-plated metals	−0.45
10	Tin–lead, solid, plated or fused	−0.50
11	Lead, solid or plated; high lead alloys	−0.55
12	Aluminium–copper alloys (e.g. Duralumin and most of AA 2xxx series)	−0.60
13	Iron, wrought, grey or Armco; plain carbon and low alloy steels	−0.70
14	Aluminium and most alloys other than in Group 12 (e.g. AA 1xxx, 3xxx and 5xxx series)	−0.75
15(a)	Cast aluminium alloys other than aluminium–silicon type	−0.80
15(b)	Cadmium plating	−0.80
16	Hot dipped zinc plate	−1.05
17	Zinc, wrought; zinc-based casting alloys; zinc plating	−1.10
18	Magnesium and magnesium-based alloys, cast or wrought	−1.60

* Calomel electrode/sea water. For reasonable galvanic compatibility, the maximum potential difference between soldered metals should be less than 0.5 V.

34.3.3 Control of corrosion

If long storage periods are expected between manufacture of components and solder assembly, the surfaces of the common industrial metals can be plated initially with copper or nickel and subsequently with a pre-tinning eutectic composition of tin–lead solder which can be fused in hot oil to form a 4–12 μm thick pore-free protective layer possessing excellent solderability even after many years in storage. Less active fluxes may then be employed which will reduce the need for post-soldering cleaning.

Subsequently to joining, corrosion may occur near a joint if flux residues are present. These residues are frequently hygroscopic and can cause severe discoloration or worse problems in the joint locality given only the presence of atmospheric humidity. It is therefore essential to clean off flux residues, preferably as soon as possible after soldering. The choice of cleaning agent will depend on the type of joint, the flux used and the extent to which cleanliness is critical.

If aqueous fluxes are used, the simplest wash is to quench the joint in water prior to inspection and possible further cleaning. Pickling in dilute acid is sometimes used but the active surface left by this aggressive process must be subsequently passivated. For cleaning organic residues a variety of solvents are possible and the recommendations of the flux manufacturer should be followed in the absence of any other process standard.

In service it is possible to suffer galvanic corrosion if dissimilar metals are exposed in damp or wet service or storage environments. In any bi-metallic couple the more noble metal will not be corroded but the less noble will be attacked at a rate dependent on the environment and the electrical potential difference between the metals. Its effect may be reduced if the area of the less noble, or sacrificial metal is significantly greater than the noble metal. Fortunately tin–lead, the most common soldering alloy, is generally compatible with most solderable metals, except gold. The galvanic series is useful as a first approximation in selecting materials for both solderability and corrosion control, but for many applications it may be too simplistic because it does not provide information about corrosion rates or changes in surface chemistry which may pacify or accelerate corrosion at bi-metallic interfaces.

34.3.4 Solder formulations

Generally, solder alloys are based on the metals tin, lead, cadmium, zinc and indium. They are available in a variety of physical forms to facilitate different means of application. Solder ingots are used to replenish large baths for dip or wave-soldering. Solder creams, containing a gel of solder powder, flux and wetting agent, can be painted or screen-printed for microelectronic applications. Preforms of solder are used for furnace and torch-soldering and include formed wires and parts punched from flat sheet.

Solder alloys can be divided into four groups according to their melting ranges. Melting temperatures are not recommended soldering temperatures. Typically, 20–70°C above the liquidus temperatures ensures good alloy fluidity and wetting characteristics. Compositions, melting ranges, and typical uses for these types are given in Tables 34.4 to 34.7.

Table 34.4 VERY LOW MELTING POINT SOLDERS (BELOW 183°C)
Uses include joining heat-sensitive components or adding components to existing circuits (one solder operation on another where second soldering does not remelt initial joint). Contamination with certain other solder compositions may cause alloying and even lower melting temperatures.

Nominal composition							*Melting range*	
Sn	Pb	Sb	Bi	Cd	In	Ag	°C	*Name*
49	33	—	—	18	—	—	145 m.p.	BS 219, Grade 'T' (DIN 1707, L-SnPb Cd 18)
50	—	—	—	—	50	—	117–125	Glass-to-metal sealing (L-SnIn 50)
14.5	28.5	9	48	—	—	—	103–227	Matrix alloy
22	28	—	50	—	—	—	96–110	Rose's
13	27	—	50	10	—	—	70–73	Lipowitz's
12.5	25	—	50	12.5	—	—	70–72	Bending (Wood's)
8.3	22.6	—	44.7	5.3	19.1	—	47 m.p.	—
12.8	25.6	—	48	9.6	4	—	62 m.p.	—
—	—	—	—	27	73	—	123 m.p.	—
37.5	37.5	—	—	—	25.0	—	134–174	—
—	15	—	—	—	80	5	149 m.p.	—
13	27	—	50	10	—	—	70 m.p.	Quaternary eutectics
26	—	—	54	20	—	—	103 m.p.	Ternary eutectics
—	—	—	60	40	—	—	144 m.p.	Binary eutectics

Table 34.5 COMMON SOLDER ALLOYS (183–270°C)

Nominal composition			*Melting range* °C	*Specification BS 219:1977*	*Typical uses*
Sn	Pb	*Other*		*grade*	*(similar alternative standard)*
Tin solders					
63	37	0.6Sb max	183 m.p.	A	Soldering of electrical connections to copper, brass and zinc. Capillary joints in copper and stainless steel (QQ-S-571d, type Sn63)*
63	37	0.2Sb max	183 m.p.	AP	As 'A', but for higher reliability on printed circuit boards (DIN 1707 L-Sn63Pb) (ESA QRM-08, Sn63)*
60	40	0.5Sb max	183–188	K	As 'A', but also for pre-tinning of electrical components (DIN 1707 L-Sn60PbSb) (QQ-S-571d, type Sn60)
60	40	0.2Sb max	183–188	KP	Hand and machine-soldering of electronics and pre-tinning (DIN 1707 L-Sn60Pb) (ESA QRM-08, Sn60) (ASTM-B-32-66T-60A)
50	50	0.5Sb max	183–212	F	General engineering work on copper, brass and zinc. Can-soldering (DIN 1707 L-Sn50Pb(Sb), etc.)
45	55	0.4Sb max	183–224	R	
40	60	0.4Sb max	183–234	G	

Table 34.5 COMMON SOLDER ALLOYS (183–270°C)—*continued*

Nominal composition			*Melting range* °C	*Specification BS 219: 1977 grade*	*Typical uses (similar alternative standard)*
Sn	Pb	*Other*			
35	65	0.3Sb max	183–244	H	Joining of electrical cable sheaths (DIN 1707 L-PbSn35(Sb))
30	70	0.3Sb max	183–255	J	
20	80	0.2Sb max	183–276	V	Lamp solder. Dip-soldering. For low temperature service (also BS 441-20)
15	85	0.2Sb max	227–288	W	
100	—	—	232 m.p.	(BS 2352)	Food-handling equipment and cans
Tin–lead–antimony					
50	50	2.5–3.0Sb	185–204	B	Hop dip coating and soldering of ferrous metals; jointing of copper conductors
45	55	2.2–2.7Sb	185–215	M	
40	60	2.0–2.4Sb	185–277	C	General engineering. Heat exchanges. General dip-soldering
32	68	1.6–1.9Sb	185–243	L	Plumbing, wiping of lead and lead alloy cable-sheathing. Dip-soldering
30	70	1.5–1.8Sb	185–248	D	
18	82	0.9–1.1Sb	185–275	N	Dip-soldering (also BS AU90-19A)
Tin–antimony					
95	—	4.75–5.25Sb	236–243	95A	High service temperatures (more than 100°C) and refrigeration equipment. Step-soldering
Tin–silver					
96	0.10 max	3.5–3.7Ag	221 m.p.	96S	High service temperatures (more than 100°C)
97	0.10 max	3.0–3.5Ag	221–223	97S	Intended for making capillary joints in copper plumbing systems for potable water applications where the lead content of the solder is restricted
98	0.10 max	1.8–2.2Ag	221–230	98S	
Tin–copper					
99	—	0.45–0.85Cu	227–228	99C	
Tin–lead–silver					
5	Rest	1.4–1.6Ag	296–301	5S	For service at high (> 100°C) and low (< −60°C) temperature
62.5	Rest	1.8–2.2Ag	178 m.p.	62S	Soldering of silver-coated substrates (ESA QRM-08, 62Sn) (approx. DIN 1707 L-Sn60PbAg) (QQ-S-571d, Sn62)
Solder for aluminium					
90	—	10Zn	200–210	—	Soldering aluminium by ultrasonics (DIN 8512 L-SnZn10)
60	—	40Zn	200–300	—	Frictional soldering of aluminium (DIN 8512 L-SnZn40)
Gold–tin alloy					
20	—	80Au	280 m.p.	—	Micro-electronics manufacturing
Lead–indium alloys					
—	50	50In	215–230	—	Hybrid micro-electronics (thick-thin film substrates). Prevents scavenging of gold
—	75	25In	173–190	—	

* Eutectic type solders with single discrete melting point; they solidify with smooth bright fillets which can be readily inspected—recommended for highly reliable electrical connections. These are used for hand or machine soldering of printed circuit boards but care should be taken to avoid trace impurities, e.g. Zn or Al <0.005% to prevent oxide skin; Fe or Au or Cu or As or Sb <0.2% to prevent hard or embrittled joints.

34.3.5 Cleaning

Soldered joints should be cleaned after completion in order to prevent surface corrosion and stress corrosion cracking. Cleaning also facilitates inspection. Immersion cleaning is improved by ultrasonic agitation.

Subject to manufacturers' recommendations or other process control specifications, the following solvents are acceptable for the cleaning of electronic equipment provided cleaning takes place

Table 34.6 INTERMEDIATE TEMPERATURE SOLDERS (270–370°C)
Elevated temperature applications where some creep strength is required.

The lead-based alloys, which contain additions of up to 8% tin and/or silver, may be used to about 130°C. Higher service temperatures may be satisfied by selecting tin-free lead alloys, but these have poor wetting properties and require the use of special organic fluxes which will not decompose at the high soldering temperatures. Alloys containing in excess of 90% lead are selected for cryogenic applications because they retain ductility and can take up mismatches in thermal expansion at the low temperatures. The final inspection of cleaned connections made with these alloys may reveal high contact angles and dull surface finishes, but these should not be construed as a sign of cold solder joints.

Nominal composition						*Melting range* °C	*Name*
Sn	Pb	Sb	Ag	Cd	Zn		
2	98	—	—	—	—	320–325	DIN 1707, L-PbSn2
5	93.5	—	1.5	—	—	296–301	BS 219, Grade 5S and BS AU90-5S
8	91.7	0.3	—	—	—	280–305	DIN 1707, L-PbSn8(Sb)
—	—	—	2.0	82	16	270–280	DIN 1707, L-CdZnZg2
—	—	—	10	68	22	270–380	DIN 1707, L-CdZnAg10
—	97.5	—	2.5	—	—	304–305	DIN 1707, L-PbAg3
2	96.2	—	1.8	—	—	304–310	DIN 1707, L-PbAg2Sn2
70	—	—	—	—	30	200–300	Solder for aluminium (by friction when liquid)
—	—	—	—	40	60	265–350	DIN 8512, L-ZnCd40 (frictional soldering of aluminium)
3	97	5	—	—	—	245–284	BS AU90-3AX (automobile body-filling)

Table 34.7 HIGH TEMPERATURE SOLDERS (370–430°C)*

Nominal composition wt %						
Sn	Zn	Al	Cd	Ag	*Melting range* °C	*Name*
73 (87)	8 (15)	5 (12)	—	—	193–510, depending on alloy composition	General purpose solder for aluminium alloys (MIL-S-12204, Comp. C)
—	95	5	—	—	380 m.p.	High strength solder for aluminium
—	100	—	—	—	418 m.p.	High strength solder for aluminium
—	—	—	95	5	337–393	General purpose (DIN 1707, L-CdAg5)
19	81	—	—	—	195–385	General purpose (DIN 1707, L-ZnSn20)

* Rarely used because of high dissolution of many base metals into the solder. Rapid tarnishing of adjacent areas to the joint unless special protection by flux or inert gas is provided. Only high temperature stable inorganic fluxes useful.

immediately after the soldering operation (e.g. before the flux and residues have had time to polymerize or age):

1. Ethyl alcohol, 99.5 or 95% pure by volume.
2. Isopropyl alcohol, 99% pure.
3. Trichlorotrifluorethane, clear, 99.8% pure.
4. Any mixture of the above.
5. De-ionized water at 40°C maximum may be used for certain fluxes. Items shall be thoroughly dried directly after the use of de-ionized water.

34.3.6 Product assurance

Acceptable solder connections are generally characterized as:

1. Clean, smooth, undisturbed surfaces.
2. Concave fillets between solder and joined surfaces.
3. Complete wetting as evidenced by a low contact angle between the solder and the joined surfaces.

Unacceptable solder conditions, which may be cause for rejection, are:

1. Damaged, crushed, cracked, melted, corroded, etc. surfaces.
2. Improper tinning.
3. Flux residues or other contamination.
4. Cold joints, as shown by the contact angle.
5. Fractured joints.
6. Pits, holes or voids in the joint which are not attributable to liquid-to-solid solder shrinkage.
7. Excessive or insufficient solder.
8. Splattering of flux or solder on adjacent areas.
9. De-wetting, etc.

34.4 Brazing

34.4.1 General design consideration

Brazing is a very useful technique for making permanent, strong joints between metals at moderately elevated temperatures without fusing the parent metals themselves. It should be considered when one or more of the following design requirements must be met:

1. Joints will be loaded in shear.
2. For the joining of thin sections to heavy sections.
3. For joining of sections too thin for welding.
4. When hermetically sealed assemblies are required.
5. For joints with low distortion and minimal residual stress distribution.
6. For high volume production.
7. For joining dissimilar metal combinations which cannot be welded.
8. For producing complex, permanent assemblies with multiple joints which would be inaccessible to welding.

34.4.2 Joint design

Normally only small or medium sized assemblies can be brazed as the heat required to melt the braze alloy must be applied to a broad, or usually the entire area of the component parts being joined.

Both lap and butt joints can be made with flat or tubular parts. *The strength of the join depends on the amount of bonding surface.* The simple butt joint will have a small bonding area that will not exceed the cross-sectional area of the thinner member and this type of joint is therefore not recommended. The preferred type of joint loading is in shear and lap or lap-butt joints are the most reliable. The joint should be designed to prevent stress from being concentrated at a single point. Most of the specialized textbooks and codes of good practice include diagrams showing the optimum ways in which joints such as lap-butt, tees, corners, tube-to-tube, tube caps and tube-through-plate can be designed considering the process to be used. For joints in metals such as aluminium and its alloys, tapering clearances are required to enable fluxes to float clear rather than be entrapped.

During the brazing operation provisions must be made to hold the various components to be joined. This is best done by using an interlocking design where alignment is obtained by fitting parts into each other under gravity but if this is not possible, jigs or fixtures will be needed. Parts may also be positioned by means of spot or tack welding, crimping and pinning.

The joint clearance, which is the dimension between the interfaces of the completed brazed joint, has a direct bearing on the mechanical strength of any brazed joint. Normally the highest strengths are obtained with the smallest possible thickness of filler and this is particularly true where there is little or no solubility of the parent material in the braze filler (e.g. stainless steels brazed with silver- or copper-based alloys). More clearance is required if material solubility exists, particularly in furnace brazing when long heating cycles are required (e.g. austenitic stainless steels brazed with nickel fillers).

It is extremely important to plan a joint clearance based on the brazing temperatures and not room temperature. The coefficients of expansion of the metals being joined must be taken into account, especially in tubular assemblies in which dissimilar metals are being joined. If the metal with the greater expansion coefficient is on the inside there may be no clearance at the brazing temperature and under reverse conditions a room temperature gap can become too large for adequate capillary flow at the brazing temperature.

As a design rule the filler metal should remain in slight compression once the assembly returns to room temperature. The metal having the greater coefficient of expansion is therefore normally used as the female member of the joint. Ideally, parts to be brazed should have a similar coefficient of expansion in order to facilitate joint clearance calculation and prevent the generation of large residual stresses caused by badly matched materials. The optimum joint clearance will depend on the nature and sizes of the parts being joined, the heating methods and the configuration of the joint itself. As there are many variables involved in assuming the actual clearance at brazing temperatures it is recommended that simple calculations are made utilizing the coefficients of expansion presented in Table 34.8 and these are followed up by trial operation using representative test samples. For most brazing alloys effective capillary action occurs when the braze path gap at the brazing temperature is maintained within the range 0.025–0.200 mm. Table 34.9 may also be used as a guide.

Table 34.8 COMPARISONS OF MATERIALS: COEFFICIENT OF THERMAL EXPANSION[a]

	$10^{-5}\,K^{-1}$	
Material	*High*	*Low*
Aluminium and its alloys[c]	2.5	2.1
Aluminium bronzes (cast)[c]	1.7	1.6
Alumina ceramics[a]	0.7	0.6
Alumina cermets[d]	0.9	0.8
Beryllia[e]	0.9	—
Beryllium[b]	1.1	—
Beryllium carbide[d]	1.0	—
Beryllium copper[c]	1.7	—
Boron carbide[e]	0.3	—
Boron nitride[d]	0.8	—
Brasses—plain and leaded[c]	2.1	1.8
Bronzes (cast)[c]	1.8	1.8
Carbon[c]	0.3	0.2
Chromium carbide cermet[c]	1.1	1.0
Cobalt[d]	1.2	—
Coppers[c]	1.8	—
Copper–nickel alloys[c]	1.7	1.6
Graphite[c]	0.3	0.2
Gold[c]	1.4	—
Hafnium[b]	0.6	—
Heat resistant alloys (cast)[d]	1.9	1.1
Iridium[b]	0.7	—
Iron—cast (grey)[c]	1.1	—
—cast, nodular or ductile[d]	1.9	1.2
—malleable[c]	1.3	1.1
—wrought[c]	1.3	—
Lead and its alloys[c]	2.9	2.6
Magnesium alloys[b]	2.8	2.5
Molybdenum and its alloys	0.6	0.5
Molybdenum disilicide[e]	0.9	—
Nickel and its alloys[d]	1.7	1.2
Nickel alloys—low expansion[c]	1.0	0.3
Nickel silvers[c]	1.7	1.6
Niobium and its alloys	0.7	0.68
Osmium[b]	0.6	—
Palladium[c]	1.2	—
Phosphor bronzes[c]	1.8	1.7
Platinum[c]	0.9	—
Rhodium[b]	0.8	—
Ruthenium[b]	0.9	—
Silicon carbide[e]	0.4	0.39
Silver[b]	2.0	—
Steatite[c]	0.7	0.6

Table 34.8 COMPARISONS OF MATERIALS: COEFFICIENT OF THERMAL EXPANSION[a] *—continued*

Material	$10^{-5}\ K^{-1}$ *High*	*Low*
Steels—alloy[d]	1.5	1.1
—alloy (cast)[d]	1.5	1.4
—carbon, free cutting[d]	1.5	1.5
—high temperature[d]	1.4	1.1
—nitriding[d]	1.2	—
—stainless (cast)[d]	1.9	1.1
—stainless (austenitic)[c]	1.8	1.6
—stainless (ferritic)[c]	1.1	1.0
—stainless (martensitic)[c]	1.2	1.0
—ultra high strength[d]	1.4	1.0
Superalloys—Cr–Ni–Fe[d]	1.9	1.7
—Cr–Ni–Co–Fe[d]	1.6	1.4
—cobalt based[d]	1.7	1.2
—nickel base	1.8	1.4
Tantalum[b]	0.6	—
Tantalum carbide[d]	0.8	—
Thoria[e]	0.9	—
Thorium[b]	1.1	—
Tin and its alloys[b]	2.3	—
Titanium and its alloys[d]	1.3	0.9
Titanium carbide[d]	0.7	—
Titanium carbide cermet[d]	1.3	0.8
Tungsten[b]	0.4	—
Tungsten carbide cermet[e]	0.7	0.4
Vanadium[b]	0.9	—
Zinc and its alloys[c]	3.5	1.9
Zircon[c]	0.3	0.2
Zirconia[e]	0.6	—
Zirconium and its alloys[b]	0.6	0.55
Zirconium carbide[d]	0.7	—

[a] Values represent high and low sides of a range of typical values.
[b] Value at room temperature only.
[c] Value for a temperature range between room temperature and 100–390°C.
[d] Value for a temperature range between room temperature and 540–980°C.
[e] Value for a temperature range between room temperature and 1 205– 1 508°C.

Based on data from 'Materials Selector', Reinhold Publishing Co., Penton/IPC; *see* also Chapter 14—General physical properties.

Table 34.9 RECOMMENDED JOINT CLEARANCES (mm)

Brazing material	*Copper*	*Copper-base alloys*	*Ferrous metals*	*Aluminium and its alloys*
Noble metal alloys[a]	0.025–0.10	0.025–0.10	0.025–0.1	—
Copper	—	—	Nil–0.075	—
Brasses	0.075–0.375	0.075–0.375	0.05–0.25	—
Copper–phosphorus	0.075–0.375	0.075–0.375	—	—
Silver–copper–phosphorus	0.05–0.30	0.05–0.30	—	—
Silver brazing alloys	0.03–0.25	0.03–0.25	0.025–0.15	—
Nickel-base alloys	—	—	0.075–0.375[b]	—
Aluminium brazing alloys	—	—	—	0.125–0.6

[a] Ensure that the solidus value of the parent metal is at least 100°C above the liquidus of the selected brazing material.
[b] Special formulations are available which will permit wider gaps than 0.375 mm to be brazed in a satisfactory manner.
Reprinted from Brooker and Beatson, 'Industrial Brazing', 2nd edn, Newnes-Butterworth, 1975.

34.4.3 Precleaning and surface preparation

Uniform capillary action may only occur when all grease, oil, oxides and dirt have been removed from both the base metals and braze alloy. Fluxes cannot be relied upon to clean the area to be brazed—they are mainly intended to prevent the formation of oxides during brazing and reduce the surface tension of the filler metal. Cleaning may be performed by chemical, mechanical or vacuum methods. Chemical cleaning is most frequently carried out utilizing commercial solvents, vapour degreasing, alkaline mixtures (detergents, soaps, carbonate, hydroxides), electrolytic methods (anodic and cathodic), acidic solutions and salt bath pickling. Mechanical cleaning methods include grinding, filing, machining, shot blasting and ultrasonics. In all cases care must be taken to avoid the embedment of oxides or ferrous materials into the surfaces to be brazed as these will interfere with the proper wetting of the base metal by the liquid braze alloy. Very smooth, polished surfaces are less satisfactory for brazing than slightly roughened surfaces.

34.4.4 Positioning of filler metal

Dependent on the design of the joint and the type of heating technique used, the braze filler metal may be pre-placed prior to heating or applied when the joint is at temperature. It may be in the form of wire, ring, shim, clad sheet, powder, paste or slurry, depending upon the specific application and process. These forms of filler metals can be positioned by grooves, shoulders and/or recesses which serve as reservoirs for filling the braze paths. Designs of joint suitable for hand feeding will be different from those used when pre-formed inserts of brazing filler are used. In the latter case, the manufacturers of the fillers are generally glad to advise on optimum joint design and for the positioning of the components to allow for movement as the pre-form melts.

All braze assemblies should be designed so that the parent metals and the filler metals are uniformly heated when component parts have different thermal capacities. Two-stage heating with long dwell times may be necessary to ensure that liquation and flow of the filler metal occur simultaneously in all locations. Gravity flow of the filler metal through the braze path should be provided when possible. Machined grooves should be provided when large ($> 50\ mm^2$) flat surfaces are united by brazing. Unless full penetration by the brazing alloy is achieved, an internal crevice will remain as a potential site for flux and residue. In certain configurations the presence of visible filler metal fillets will aid inspection.

34.4.5 Heating methods

TORCH BRAZING

Parts should be pre-heated with a neutral or slightly reducing flame so that uniform heating or the surfaces to be joined can be achieved. Localized overheating must be avoided. Flux is usually applied (some proprietary fluxes indicate the part's surface temperature by a colour change) and the braze alloy is introduced at one of the mating surfaces. Torch brazing is frequently used for the attachment of small parts on to large surfaces, one-off jobs and repairs. Automation, generally on a rotary table, is not difficult when long production runs are planned.

FURNACE BRAZING

This process can frequently be employed with the use of little or no flux, dependent on the materials being brazed and the extent to which the furnace atmosphere is kept reducing in character. Where possible, the furnace atmosphere should be strictly controlled, particularly with respect to the hydrogen potential and the dew point which should be instrumented for continuous control. Braze alloy pre-forms are located between pre-assembled parts which are usually fluxed and self-jigging.

Vacuum furnaces may be used, employing pressures of 1.0 to 1.0×10^{-9} torr and being heated either by radiation from resistance elements or by induction coils. Metal–metal oxide equilibrium diagrams are useful to show the relationship which exists between the furnace operating temperature and the reducing or oxidizing behaviour of the atmosphere. Figure 34.1 indicates the effect of dew point of hydrogen and partial pressure of water on the brazeability of pure metals.

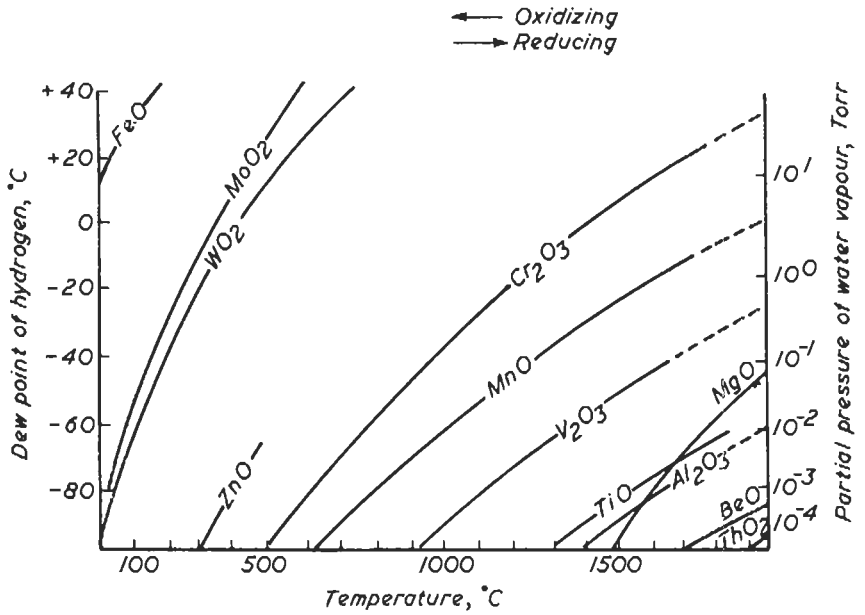


Figure 34.1 *Metal–metal oxide equilibria in hydrogen atmospheres. Oxidizing conditions exist at the left of each curve; reducing conditions which facilitate brazing exist on the right of each curve. Note Au, Pt, Ag, Pd, Ir, Cu, Co, Ni and Os oxides are easier to reduce than those plotted.*

INDUCTION BRAZING

Heating is localized, fast, and generally accomplished within one or two minutes. Coils may be shaped to follow the contours of the assembly and adjustment to the coil separation distances can cause heavier sections to heat up at the same rate as thin sections. The mating surfaces can be coated with flux, or pre-assembled units with braze alloy pre-forms may be heated in a suitable atmosphere. It must be remembered that high-resistance metals such as steel heat up rapidly whereas low-resistance metals take longer to reach the brazing temperature. Amongst other factors, the efficiency of heating is controlled by the frequency of the equipment which should be suitable for the size of assemblies normally expected.

ELECTRIC RESISTANCE BRAZING

This technique is suitable only for relatively small joint areas because it is difficult to maintain uniform current distributions. Localized heating does not usually modify the mechanical properties of the parent metals. Success will depend upon the thermal capacities and thermal conductivities of the metals being joined. The presence of an intermediate layer of flux can be detrimental if direct heating is employed (i.e. when heating current passes through two work pieces sandwiching the brazing alloy). Once the optimum brazing schedule has been established this method can become semi-automated and requires minimal operator skills.

SALT BATH DIP BRAZING

The assembled joint, with the filler metal(s) preplaced, is dipped into a bath of molten salt which acts as flux. Occasionally the parts may be dipped into a bath of molten brazing alloy covered with a layer of flux. Dip brazing is widely used for joining aluminium components. Preheating of parts is recommended as it prevents excessive freezing of the salt on a cold surface, expels water entrapped within the assembly thereby minimizing the risk of explosions from immersed parts, and markedly increasing the speed of production. The specific gravity of the molten salt used is close

to that of aluminium, reducing by half the weight of submerged pieces. This facilitates the dip-brazing of complex aluminium assemblies that are not strong enough to be self-supporting when brazed by other techniques. Personnel must of course wear protective clothing and face masks.

34.4.6 Brazeability of materials and braze alloy compositions

It is not possible to detail the optimum heating methods and filler metals for the wide range of base metals and combinations of base metals. Expert advice should be sought or literature searches and experimentation must be performed prior to the brazing of uncommon materials. It is strongly recommended that the referenced Standards are consulted for additional information. The brazing alloy systems in common use are listed in Table 34.10 with compositions detailed in Table 34.11.

A useful guide to the suitability of parent materials and filler metals for torch brazing, furnace brazing, induction brazing, electrical resistance brazing, and vacuum brazing is presented in Tables 34.12 to 34.16.

34.5 Bibliography and sources of information

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British Standards Institution, Sales Office, Information Department and Technical Help to Exporters, Linford Wood, Milton Keynes MK14 6LE.
American specifications: American Technical Publications, 68a Wilbury Way, Hitchin, Herts SG4 0TP.
International Tin Research Institute, Kingston Lane, Uxbridge, Middx U88 3PJ.
British Association for Brazing and Soldering, The Welding Institute, Abington Hall, Abington, Cambridge CB1 6AL.
Copper Development Association, Orchard House, Mutton Lane, Potters Bar, Herts EN6 3AP.
Printed Circuit Group, Institute of Metal Finishing, Exeter House, 48 Holloway Head, Birmingham B1 1NQ.
DTI Soldering Club, National Physical Laboratory, Teddington. Middx.
Lead Development Association, 42 Weymouth Street, London W1N 3LQ.
Low melting point solders: Mining and Chemical Products Ltd, 38 Rosemont Road, Alperton, Wembley, Middx HA0 4PE.
Solders: Fry's Metals Ltd, Tandem Works, Christchurch Road, Wimbledon, London SW19 2PD and United Alloys Ltd, Crosslands Lane North Cave, Brough HU15 2PG.
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Table 34.10 COMMON BRAZING-ALLOY SYSTEMS (BASED INITIALLY ON BS 1723)

Alloy system	*Melting range* (°C)	*Refer to BS 1845 table no.*	*AWS-ASTM classification (non-exhaustive)*	*DIN designations and Werkstoff numbers (in brackets) (non-exhaustive)*
Copper	1 083	4	BCu-1	L-Cu (2.0081), L-SFCU (2.0091)
Silver	961			
Copper-zinc	860- 890	5	RBCuZn-A	L-CuZn46 (2.0413)
Bronze welding type	920- 980	5		
Copper-phosphorus	705- 800	3	BCuP-1, BCuP-2	L-CuP8 (2.1465)
Silver-copper	779	2	BAg-8	L-Ag72 (2.5151)
Copper-silver-zinc	690- 775	2	BAg-5	L-Ag44 (2.5147), L-Ag60
Copper-silver-phosphorus	644- 780	3	BCuP-3, BCuP-5	L-Ag15P (2.1210), L-Ag5P (2.1466)
Copper-silver-tin	602- 718	2		
Copper-silver-zinc-cadmium-nickel	630- 660		BAg-3	L-Ag50CdNi (2.5160)
Copper-silver-zinc cadmium	620-640	2	BAg-1, BAg-2	L-Ag50Cd (2.5143)
Cobalt-chromium-boron	984-1 240			
Nickel-chromium-boron	1 030-1 175			
Nickel-chromium-silicon-boron	950-1 100		BNi-2	
Nickel-silicon-boron	950-1 070	6	BNi-3, BNi-4	
Nickel-phosphorus	890-1 023		BNi-6	
Silver-palladium-manganese	1 000-1 200	7		(2.5154, 2.5164)
Nickel-palladium-manganese	1 120	7		(2.4304)
Copper-palladium-nickel-manganese	1 060-1 105	7		
Palladium-nickel	1 237			
Copper-nickel	1 100-1 150			
Copper-palladium	1 080-1 090	7		
Silver-palladium	970-1 010	7		
Silver-copper-palladium	807- 950	7		
Gold-nickel	950	8	BAu-4	
Gold-copper	910	8	BAu-1, BAu-2	
Aluminium-silver-nickel (or manganese)	558- 680			
Aluminium-silicon	565- 625	1	BAlSi-2, BAlSi-4	L-AlSi12 (3.2285)
Aluminium-silicon-copper	550- 570	1	BAlSi-3	

Note: Some alloys are available in only one specific form and this should be ascertained before joint-design is considered. The available forms are wire, foil, powder, clad sheet, deposited coating and, in many cases, paste.

Table 34.11 FILLER METALS FOR BRAZING* (*SEE* BS 1845 FOR FULL COMPOSITION AND REQUIREMENTS)

Designation		*Nominal composition (%) (excluding impurities)*											*Melting range*
BS 1845	*ISO*	Cu	Ag	Zn	P	Cd	Sn	Mn	Ni	Sb	Bo	Si	(°C)
Group AG: silver brazing filler metals													
AG1	—	15	50	15	—	19	—	—	—	—	—	—	620–640
AG2	—	17	42	15	—	25	—	—	—	—	—	—	610–620
AG3	—	20	38	22	—	20	—	—	—	—	—	—	605–650
AG11	—	25	34	20	—	21	—	—	—	—	—	—	610–670
AG12	—	28	30	21	—	21	—	—	—	—	—	—	600–690
AG14	—	21	55	22	—	—	2	—	—	—	—	—	630–660
AG20	—	30	40	28	—	—	2	—	—	—	—	—	650–710
AG21	—	36	30	32	—	—	3	—	—	—	—	—	665–755
AG5	—	37	43	20	—	—	—	—	—	—	—	—	690–770
AG7	—	28	72	—	—	—	—	—	—	—	—	—	780
AG9	—	15	50	15	—	16	—	—	3	—	—	—	635–655
AG13	—	26	60	14	—	—	—	—	—	—	—	—	695–730
AG18	—	16	49	23	—	—	—	7	4	—	—	—	680–705
AG19	—	—	85	—	—	—	—	15	—	—	—	—	960–970
Group CP: copper–phosphorus brazing filler metals													
CP1	CuAg14P5	Rem.	14.5	—	4.5	—	—	—	—	—	—	—	645–800
CP2	CuP6Ag2	Rem.	2	—	6.5	—	—	—	—	—	—	—	645–825
CP3	CuP7	Rem.	—	—	7.5	—	—	—	—	—	—	—	710–810
CP4	CuP6Ag5	Rem.	5	—	6	—	—	—	—	—	—	—	645–815
CP5	CuP6Sb	Rem.	—	—	6	—	—	—	—	2	—	—	690–825
CP6	CuP6	Rem.	—	—	6	—	—	—	—	—	—	—	710–890
Group CU: copper brazing filler metals													
CU2 (C102)	Cu-FRTP	99.90	—	—	—	—	—	—	—	—	—	—	1085
CU3 (C103)	Cu-OF	99.95	—	—	—	—	—	—	—	—	—	—	1085
CU5	—	99.00	—	—	—	—	—	—	—	—	—	—	1085
CU6 (C106)	Cu-DHP	99.85	—	—	0.02	—	—	—	—	—	—	—	1085
CU7	CuNi3	Rem.	—	—	—	—	—	—	3	—	0.03	—	1085–1100
CU8	CuMn2	Rem.	—	—	—	—	—	2	—	—	—	—	1045–1060
Group CZ: copper–zinc brazing filler metals													
CZ6	CuZn40Si	60	—	Rem.	—	—	—	—	—	—	—	0.3	875–895
CZ6A	CuZn40SiSn	60	—	Rem.	—	—	0.3	—	—	—	—	0.3	875–895
CZ7	CuZn40SiMn	60	—	Rem.	—	—	—	0.1	—	—	—	0.3	870–900
CZ7A	CuZn40SiSnMn	60	—	Rem.	—	—	0.3	0.1	—	—	—	0.3	870–900
CZ8	CuZn43Ni9Si	48	—	Rem.	—	—	—	—	9	—	—	0.3	920–980

* Applications for these materials are described in CDA publication TN 25 'Joining of Copper and Copper Alloys'.

Table 34.12 COMBINATIONS OF PARENT MATERIAL AND FILLER METAL FOR FLAME (TORCH) BRAZING*

	Filler metal																												
Parent material	Copper	Silver	Copper–zinc	Bronze welding type	Copper–phosphorus	Silver–copper	Copper–silver–zinc	Copper–silver–phosphorus	Copper–silver–tin	Copper–silver–zinc–cadmium–nickel	Copper–silver–zinc–cadmium	Cobalt–chromium–boron	Nickel–chromium–boron	Nickel–chromium–silicon–boron	Nickel–silicon–boron	Nickel–phosphorus	Silver–palladium–manganese	Nickel–palladium–manganese	Copper–palladium–nickel–manganese	Palladium–nickel	Copper–nickel	Copper–palladium	Silver–palladium	Silver–copper–palladium	Gold–nickel	Gold–copper	Aluminium–silver–nickel (or manganese)	Aluminium–silicon	Aluminium–silicon–copper
Copper	N	R	R	R	R	R	R	R	P	R	R	N	N	N	N	N	N	N	N	N	N	N	N	R	P	R	N	N	N
Copper-base alloys	N	R	P	P	R	R	R	R	P	R	R	N	N	N	N	N	N	N	N	N	N	N	N	R	P	R	N	N	N
Mild steel	N	P	R	R	N	P	R	N	P	R	R	P	R	R	R	N	R	R	P	P	N	R	R	R	P	P	N	N	N
Carbon steels	N	P	R	R	N	P	R	N	N	R	R	P	R	R	R	N	R	R	P	P	N	R	R	R	P	P	N	N	N
Alloy steels	N	P	R	R	N	P	R	N	N	R	R	P	R	R	R	N	R	R	P	P	N	R	P	R	P	P	N	N	N
Stainless steels and irons	N	N	R	R	N	N	R	N	P	R	R	P	R	R	R	N	R	R	R	P	N	R	P	R	P	P	N	N	N
Malleable iron	N	N	R	R	N	N	P	N	N	R	R	N	N	N	N	N	P	P	P	P	N	R	P	P	P	P	N	N	N
Wrought iron	N	N	R	R	N	N	P	N	N	R	R	N	N	N	N	N	P	P	P	P	N	R	P	P	P	P	N	N	N
Cemented carbides	N	N	R	R	N	N	P	N	N	R	R	N	P	P	P	N	P	P	P	P	N	P	N	P	P	P	N	N	N
Nickel-base alloys	N	N	R	R	N	N	R	N	N	R	R	P	R	R	R	N	R	R	R	P	N	R	P	R	P	P	N	N	N
Cobalt-base alloys	N	N	P	R	N	N	P	N	N	P	P	P	P	P	P	N	P	P	P	P	P	P	P	N	P	P	N	N	N
Aluminium and certain aluminium alloys	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	R	R
Tungsten	N	N	P	P	P	P	R	P	P	R	R	N	P	P	P	N	P	P	P	N	N	N	P	P	P	P	N	N	N
Molybdenum	N	N	P	P	P	P	R	P	P	R	R	N	P	P	P	N	P	P	P	N	N	N	P	P	P	P	N	N	N
Titanium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P
Zirconium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Tantalum	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Beryllium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N
Niobium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N

R—Recommended and known to be in general use. It should be recognized, however, that in many instances jointing by brazing results in a weakening of the parent material due to intercrystalline penetration, grain growth and other causes.

P—Possible but not known to be in general use.

N—Not recommended.

* From BS 1723.

Table 34.13 COMBINATIONS OF PARENT MATERIAL AND FILLER METAL FOR FURNACE BRAZING*

	Filler metal																												
Parent material	Copper	Silver	Copper–zinc	Bronze welding type	Copper–phosphorus	Silver–copper	Copper–silver–zinc	Copper–silver–phosphorus	Copper–silver–tin	Copper–silver–zinc–cadmium–nickel	Copper–silver–zinc–cadmium	Cobalt–chromium–boron	Nickel–chromium–boron	Nickel–chromium–silicon–boron	Nickel–silicon–boron	Nickel–phosphorus	Silver–palladium–manganese	Nickel–palladium–manganese	Copper–palladium–nickel–manganese	Palladium–nickel	Copper–nickel	Copper–palladium	Silver–palladium	Silver–copper–palladium	Gold–nickel	Gold–copper	Aluminium–silver–nickel (or manganese)	Aluminium–silicon	Aluminium–silicon–copper
Copper	N	R	R	N	R	R	R	R	R	R	R	N	N	N	N	N	N	N	N	N	N	N	R	R	R	N	N	N	
Copper-base alloys	N	R	P	N	R	R	R	R	R	R	R	N	N	N	N	N	N	N	N	N	N	N	R	R	R	N	N	N	
Mild steel	R	P	R	R	N	R	R	N	R	R	R	P	R	R	R	N	R	R	R	R	R	R	R	R	R	N	N	N	
Carbon steels	R	P	R	R	N	R	R	N	R	R	R	R	R	R	R	N	R	R	R	R	R	R	R	R	R	N	N	N	
Alloy steels	R	P	R	R	N	R	R	N	P	R	R	P	R	R	R	N	R	R	P	P	R	R	P	R	P	P	N	N	
Stainless steels and irons	R	P	P	N	N	R	P	N	R	P	P	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	N	N	
Malleable iron	R	P	R	N	N	P	R	N	P	P	P	P	P	P	P	N	R	P	P	P	R	R	P	R	P	P	N	N	
Wrought iron	R	P	R	N	N	P	R	N	P	P	P	P	P	P	P	N	R	P	P	P	R	R	P	R	P	P	N	N	
Cemented carbides	R	P	P	R	N	P	P	N	P	P	P	N	P	P	P	N	P	P	R	P	P	R	P	R	P	P	N	N	
Nickel-base alloys	R	P	P	N	N	R	P	N	P	P	P	R	R	R	R	R	R	R	R	R	P	R	R	R	R	R	N	N	
Cobalt-base alloys	P	P	N	P	N	P	P	N	P	P	P	R	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	
Aluminium and certain aluminium alloys	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	R	R	
Tungsten	N	N	N	N	N	N	P	P	P	P	P	N	R	R	N	R	R	R	R	P	P	P	R	R	P	N	N	N	
Molybdenum	N	N	N	N	N	N	P	P	P	N	N	N	R	R	R	N	R	R	R	P	R	P	R	R	P	N	N	N	
Titanium	N	P	N	N	N	P	N	N	P	N	N	N	N	N	N	N	N	N	N	P	P	N	R	P	P	R	P	P	
Zirconium	N	P	N	N	N	P	N	N	P	N	N	N	N	P	P	N	P	P	P	P	P	P	P	P	P	N	P	P	
Tantalum	P	N	N	N	N	P	N	N	P	N	N	N	N	P	P	N	P	P	P	R	P	P	P	R	P	N	N	N	
Beryllium	N	P	N	N	N	P	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	P	P	R	P	N	N	N	
Niobium	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P	N	P	P	P	P	P	P	P	P	P	N	N	N	

R—Recommended and known to be in general use. It should be recognized, however, that in many instances jointing by brazing results in a weakening of the parent material due to intercrystalline penetration, grain growth and other causes.
P—Possible but not known to be in general use.
N—Not recommended.

* From BS 1723.
Note: Alloys containing zinc or cadmium require a flux.

Table 34.14 COMBINATIONS OF PARENT MATERIAL AND FILLER METAL FOR ELECTRIC INDUCTION BRAZING*

	Filler metal																												
Parent material	Copper	Silver	Copper–zinc	Bronze welding type	Copper–phosphorus	Silver–copper	Copper–silver–zinc	Copper–silver–phosphorus	Copper–silver–tin	Copper–silver–zinc–cadmium–nickel	Copper–silver–zinc–cadmium	Cobalt–chromium–boron	Nickel–chromium–boron	Nickel–chromium–silicon–boron	Nickel–silicon–boron	Nickel–phosphorus	Silver–palladium–manganese	Nickel–palladium–manganese	Copper–palladium–nickel–manganese	Palladium–nickel	Copper–nickel	Copper–palladium	Silver–palladium	Silver–copper–palladium	Gold–nickel	Gold–copper	Aluminium–silver–nickel (or manganese)	Aluminium–silicon	Aluminium–silicon–copper
Copper	N	R	P	P	P	R	R	P	P	R	R	N	N	N	N	N	N	N	N	N	N	N	N	R	R	R	N	N	N
Copper-base alloys	N	R	P	P	P	R	R	P	P	R	R	N	N	N	N	N	N	N	N	N	N	N	N	R	R	R	N	N	N
Mild steel	P	N	R	R	N	R	R	N	P	R	R	P	R	R	R	N	R	R	P	P	P	R	R	R	P	P	N	N	N
Carbon steels	P	N	R	R	N	R	R	N	P	R	R	P	R	R	R	N	R	R	P	P	P	R	R	R	P	P	N	N	N
Alloy steels	P	N	R	R	N	R	R	N	P	R	R	P	R	R	R	N	R	R	P	P	P	R	P	R	P	P	N	N	N
Stainless steels and irons	P	N	P	N	N	R	P	N	P	P	P	P	R	R	R	P	R	R	R	R	P	R	P	R	R	R	N	N	N
Malleable iron	P	N	R	R	N	P	R	N	P	P	P	P	P	P	P	N	R	P	P	N	P	R	P	R	P	P	N	N	N
Wrought iron	P	N	R	R	N	P	R	N	P	P	P	P	P	P	P	N	R	P	P	N	P	R	P	R	P	P	N	N	N
Cemented carbides	R	P	R	R	N	P	R	N	P	R	P	N	P	P	P	N	P	P	R	P	P	R	P	R	P	P	N	N	N
Nickel-base alloys	R	P	P	N	N	R	P	N	P	P	P	P	R	R	R	P	R	R	R	R	P	R	R	R	R	R	N	N	N
Cobalt-base alloys	P	N	N	N	N	P	P	P	P	P	P	P	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Aluminium and certain aluminium alloys	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P
Tungsten	N	N	P	P	P	N	R	P	P	R	R	N	P	R	R	N	P	P	P	R	N	P	P	R	R	P	N	N	N
Molybdenum	N	N	P	P	P	N	R	P	P	R	R	N	P	R	R	N	R	P	P	R	N	R	P	R	R	P	N	N	N
Titanium	N	P	N	N	N	P	P	N	N	P	P	N	N	P	N	N	N	N	N	N	N	N	N	R	P	P	P	P	P
Zirconium	N	N	N	N	N	P	P	N	N	N	N	N	N	N	N	P	P	P	P	P	P	P	P	P	P	P	N	N	N
Tantalum	N	N	N	N	N	N	N	N	P	N	N	N	N	N	N	N	P	P	P	R	P	P	P	P	P	P	N	N	N
Beryllium	N	P	N	N	N	P	N	N	N	N	N	N	N	N	N	N	P	N	N	N	N	P	P	P	P	P	P	N	N
Niobium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P	P	P	N	P	P	P	P	P	N	N	N

R—Recommended and known to be in general use. It should be recognized, however, that in many instances jointing by brazing results in a weakening of the parent material due to intercrystalline penetration, grain growth and other causes.

P—Possible but not known to be in general use.

N—Not recommended.

* From BS 1723.

Table 34.15 COMBINATIONS OF PARENT MATERIAL AND FILLER METAL FOR ELECTRIC RESISTANCE BRAZING*

	Filler metal																												
Parent material	Copper	Silver	Copper–zinc	Bronze welding type	Copper–phosphorus	Silver–copper	Copper–silver–zinc	Copper–silver–phosphorus	Copper–silver–tin	Copper–silver–zinc–cadmium–nickel	Copper–silver–zinc–cadmium	Cobalt–chromium–boron	Nickel–chromium–boron	Nickel–chromium–silicon–boron	Nickel–silicon–boron	Nickel–phosphorus	Silver–palladium–manganese	Nickel–palladium–manganese	Copper–palladium–nickel–manganese	Palladium–nickel	Copper–nickel	Copper–palladium	Silver–palladium	Silver–copper–palladium	Gold–nickel	Gold–copper	Aluminium–silver–nickel (or manganese)	Aluminium–silicon	Aluminium–silicon–copper
Copper	N	R	R	N	P	R	R	R	P	R	R	N	N	N	N	N	N	N	N	N	N	N	N	R	R	R	N	N	N
Copper-base alloys	N	R	R	N	P	R	R	R	P	R	R	N	N	N	N	N	N	N	N	N	N	N	N	R	R	R	N	N	N
Mild steel	P	P	P	N	N	P	R	N	P	R	R	P	P	P	P	N	R	R	P	P	P	R	R	R	P	P	N	N	N
Carbon steels	P	P	P	N	N	P	R	N	P	R	R	P	P	P	P	N	R	R	P	P	P	R	R	R	P	P	N	N	N
Alloy steels	P	P	P	N	N	P	R	N	P	R	R	P	P	P	P	N	R	R	P	P	P	R	P	R	P	P	N	N	N
Stainless steels and irons	P	P	P	N	N	P	R	N	P	R	R	P	P	P	P	P	R	R	R	R	P	R	P	R	R	R	N	N	N
Malleable iron	P	N	P	N	N	P	R	N	P	R	R	P	P	P	P	N	R	P	P	P	P	P	P	P	P	P	N	N	N
Wrought iron	P	N	P	N	N	P	R	N	P	R	R	P	P	P	P	N	R	P	P	P	P	P	P	P	P	P	N	N	N
Cemented carbides	P	N	P	N	N	P	R	N	P	R	R	N	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Nickel-base alloys	P	P	P	N	N	P	R	N	P	R	R	P	P	P	P	P	R	R	R	R	P	R	R	R	R	R	N	N	N
Cobalt-base alloys	P	N	P	N	N	P	P	N	P	P	P	P	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Aluminium and certain aluminium alloys	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	N	P
Tungsten	N	N	P	P	P	N	R	P	P	R	R	N	N	N	N	N	P	P	P	R	P	P	P	R	R	P	N	N	N
Molybdenum	N	N	P	P	P	N	R	P	P	R	R	N	N	N	N	N	R	P	P	R	P	R	P	R	R	P	N	N	N
Titanium	N	P	N	N	N	N	P	P	P	P	P	N	N	N	N	N	N	N	N	P	N	P	P	P	P	P	P	P	P
Zirconium	N	N	N	N	N	N	P	P	N	P	N	N	N	N	N	P	P	P	P	P	P	P	P	P	P	P	N	P	P
Tantalum	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P	P	R	P	P	P	P	P	P	N	N	N
Beryllium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	R	R	P	N	P	P	R	P	P	N	N	N
Niobium	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P	P	P	N	P	P	P	P	P	N	N	N

R—Recommended and known to be in general use. It should be recognized, however, that in many instances jointing by brazing results in a weakening of the parent material due to intercrystalline penetration, grain growth and other causes.

P—Possible but not known to be in general use.

N—Not recommended.

* From BS 1723.

Table 34.16 COMBINATIONS OF PARENT MATERIAL AND FILLER METAL FOR VACUUM BRAZING[a]

	Filler metal																												
Parent material	Copper	Silver	Copper–zinc	Bronze welding type	Copper–phosphorus	Silver[a]–copper	Copper–silver–zinc	Copper–silver[a]–phosphorus	Copper–silver[a]–tin	Copper–silver–zinc–cadmium–nickel	Copper–silver[a]–zinc–cadmium	Cobalt–chromium–boron	Nickel–chromium–boron	Nickel–chromium–silicon–boron	Nickel–silicon–boron	Nickel–phosphorus	Silver–palladium–manganese	Nickel–palladium–manganese	Copper–palladium–nickel–manganese	Palladium–nickel	Copper–nickel	Copper–palladium	Silver–palladium	Silver–copper–palladium	Gold–nickel	Gold–copper	Aluminium–silver[a]–nickel (or manganese)	Aluminium–silicon	Aluminium–silicon–copper
Copper	N	P	N	N	N	R	N	N	R	N	N	N	N	N	N	N	N	N	N	N	N	N	N	R	P	R	N	N	N
Copper-base alloys	N	P	N	N	N	R	N	N	R	N	N	N	N	N	N	N	N	N	N	N	N	N	N	R	P	P	N	N	N
Mild steel	R	P	N	N	N	R	N	N	R	N	N	P	R	R	R	N	R	R	R	P	P	P	P	R	P	P	N	N	N
Carbon steels	R	P	N	N	N	P	N	N	P	N	N	P	R	R	R	N	R	R	R	P	P	P	P	R	P	P	N	N	N
Alloy steels	R	P	N	N	N	P	N	N	P	N	N	P	R	R	R	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Stainless steels and irons	R	P	N	N	N	P	N	N	R	N	N	R	R	R	R	R	R	R	R	R	R	R	R	R	R	R	N	N	N
Malleable iron	R	P	N	N	N	P	N	N	P	N	N	P	P	P	N	P	P	P	P	P	P	P	P	P	P	P	N	N	N
Wrought iron	R	P	N	N	N	P	N	N	P	N	N	P	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Cemented carbides	R	P	N	N	N	P	N	N	P	N	N	N	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Nickel-base alloys	R	P	N	N	N	R	N	N	P	N	N	R	R	R	R	P	R	R	R	R	R	R	R	R	R	R	N	N	N
Cobalt-base alloys	P	P	N	N	N	P	N	N	P	N	N	R	P	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N
Aluminium and certain aluminium alloys	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	N	P	P
Tungsten	N	N	N	N	N	N	N	N	P	N	N	N	P	R	R	N	P	P	P	R	P	R	R	R	R	P	N	N	N
Molybdenum	N	N	N	N	N	N	N	N	P	N	N	N	P	R	R	N	P	P	P	R	P	R	R	R	R	P	N	N	N
Titanium	N	P	N	N	N	P	N	N	P	N	N	N	N	N	N	N	N	N	N	N	N	N	N	R	N	P	R	P	P
Zirconium	N	P	N	N	N	P	N	N	P	N	N	N	N	P	P	P	P	P	P	P	P	P	P	P	P	P	N	P	P
Tantalum	R	P	N	N	N	P	N	N	P	N	N	N	N	P	P	N	P	P	P	R	P	P	P	P	R	R	N	N	N
Beryllium	N	P	N	N	N	P	N	N	N	N	N	N	N	N	N	N	P	N	N	P	P	P	P	R	N	P	N	N	N
Niobium	P	P	N	N	N	P	N	N	P	N	N	N	N	P	P	N	P	P	P	P	P	P	P	P	P	P	N	N	N

[a] Some alloys contain elements which are volatile at the temperatures and pressures involved in the brazing process and caution is required under prolonged heating.

R—Recommended and known to be in general use. It should be recognized, however, that in many instances jointing by brazing results in a weakening of the parent material due to intercrystalline penetration, grain growth and other causes.

P—Possible but not known to be in general use.

N—Not recommended.

Note: This table is intended only as a guide and any further information should be obtained from the manufacturer of the filler metal.

[a] From BS 1723.

35 Vapour deposited coatings

Vapour deposition processes are of two kinds: physical vapour deposition (PVD) and chemical vapour deposition (CVD). Process details and references for elements are given in Tables 35.1 and 35.2, for oxides in Tables 35.3 and 35.4, for nitrides in Tables 35.5 and 35.6, and for carbides in Tables 35.7 and 35.8.

35.1 Physical vapour deposition

Physical vapour deposition processes use a physical effect such as evaporation or sputtering to transport material, usually a metal, from a source to the substrate to be coated. If the material is transformed (e.g. into a carbide) during transport, then the process is described as reactive. All PVD processes are carried out in a relatively high vacuum (i.e. pressure $< 10^{-4}$ Torr).

35.1.1 Evaporation (E)

The substrate to be coated is placed in a vacuum chamber with a line-of-sight to the source which is a pool of molten material. The pool is heated either by an electron beam or an arc or by resistance heating. The electron beam method is best for source materials with a high melting point.

REACTIVE EVAPORATION (RE)

The same process as evaporation except that the zone through which the evaporated species is passing contains a very small concentration of a reactive gas, usually a hydrocarbon, N_2, NH_3 or O_2. This results in the deposition of the carbide, nitride or oxide of the source material.

ACTIVATED REACTIVE EVAPORATION (ARE)

The same process as reactive evaporation except that an electrically excited plasma is established in the region where the evaporated species encounters the reactive gas.

ION PLATING (IP)

The same process as evaporation except that substrate is biassed negatively with respect to the source. This usually results in a plasma region around the substrate which can be enhanced by r.f. coupling. The ionized species actually represents only a small fraction of the total material flux.

REACTIVE ION PLATING (RIP)

The same process as ion plating except that a reactive gas (usually a hydrocarbon, N_2, NH_3 or O_2) is introduced into the flux travelling towards the substrate so that the carbide, oxide or nitride of the source material is formed.

35.1.2 Sputter plating (S)

A process in which material is transferred from a target and deposited on a substrate by means of ionic bombardment of the target. Usually the ion bombardment is achieved by establishing a d.c. or r.f. plasma at the surface of the target, although ion guns can also be used.

SPUTTER ION PLATING (SIP)

The same process as sputter plating except that the substrate has an electrical negative bias so that it is bombarded with positive ions as well as the neutral flux created by the sputtering.

REACTIVE SPUTTER PLATING (RSP)

The same process as sputter plating except that a reactive gas is introduced into the plasma region so that the transported target material reacts before it arrives at the substrate. For example, the conversion of Ti into a deposit of TiN by the introduction of nitrogen.

MAGNETRON SPUTTERING (MS)

The same process as sputter plating except that a magnetic field is used to direct the ion flux at the surface of the target.

35.1.3 Ion cleaning

An argon plasma may be used to bombard a surface with excited argon atoms. These transfer their momentum to atoms in the surface and some of these are ejected from the surface. This has the effect of gradually removing material from a surface, hence cleaning the surface. Ion cleaning is often used as a pretreatment in PVD coating.

35.2 Chemical vapour deposition

Chemical vapour deposition processes use the vapour phase to transport reactive material to the surface of a substrate where a chemical reaction occurs to form a coating, e.g. tantalum by the reaction: $TaCl_5 + H_2 \rightarrow Ta + 5HCl$. Normally the substrate is heated to activate the reaction. In many CVD processes the substrate takes no part in the formation of the coating, but in *diffusion coatings* the substrate takes part in the formation of the coating (e.g. aluminizing).

CVD processes can be divided into two groups, hot wall and cold wall, as follows:

A hot-wall reactor is a chamber which is heated from the outside so that both the chamber and the work pieces reach the reaction temperature and so become coated. Consequently there is a certain amount of redundant plating which is undesirable with expensive materials.

A cold-wall reactor is a chamber in which only the work pieces are heated, usually by induction. Only the work pieces become coated.

CVD processes are a rather diffuse group because the physical conditions for each process differ widely so that there are no standard items of equipment as there are for PVD. Many CVD processes use a reduced pressure to improve throwing power (cf. PVD).

In the references *CVD* stands for the International Chemical Vapor Depositions Conference Proceedings published by The Electrochemical Society, Vapour Deposition in the refs. refers to that title by Powell, Oxley and Blocher, J. Wiley, N.Y. 1965. Process details Tables 35.2, 35.4, 35.6, 35.8.

Plasma Activated or Enhanced Chemical Vapour Deposition (PACVD or PECVD)

The same process as CVD except that a d.c. or r.f. plasma is established around the substrate, usually to permit a low coating temperature.

Metal Organic Chemical Vapour Deposition (MOCVD)

The same process as CVD except that organometallic chemicals (e.g. trimethylgallium) are used as the feed reagents. Many organometallics have a high vapour pressure and a low decomposition temperature so that coatings can be formed at low substrate temperatures. It is particularly used for the growth of epitaxial layers.

Chemical Vapour Infiltration (CVI)

The same process as CVD except that the substrate is a porous and usually fibrous material into which the deposited material is infiltrated. It is an extremely slow process, but it leads to composites of low final porosity.

Table 35.1 PHYSICAL VAPOUR DEPOSITION OF ELEMENTS

Element	*Process**	*Coating thickness* μm	*Typical application*	*Ref.*
Ag	S	0.02–0.35	Window glass	2
	RIP		Photographic materials	6
			Foil bearings	31
Al	E	~1	IC metallization	1
	S			3
	MS	~1	Mirror coating	8
Au	IP	0.2		4
	E	0.02–0.1	Window glass, electron microscopy	7
	S	1.4	Coating micro-spheres for laser fusion	5
Bi	S		Undercoat for photographic materials	6
	E	~1		
C	TS	0.05	Conductive layers for electron microscopy	32
	Arc	350	samples	19
Co (Cr/Al)	E		Turbine blades	14, 15
Cr	3	0.1–0.6	Ceramics	11
			Plastics	12
			Ni/Cr for window glass	16
			Switch contacts	
Cu	IP	0.2	Window glass coating	4
	S	0.02	Metallization of plastics prior to electroplating	11
	MS	0.01–1.0		13
Mo	IBS		Multi-level metallization for LSI	17
	S	0.15		18
Nb	S	0.4	Superconductors	22
Ni	E, S	—	—	25
Pb	E (EG)	0.4	Pb/oxide/Pb Josephson junctions	21
Pd	E	0.06	Thermoelectric power	21
	E (EG)	0.1–0.15	Contact layer	23, 24
Pt	MS	1.0	Schottky barrier solar cells	10
	E			—
Si	IBS	0.4	Integrated circuits	—
	E			
Ta	S, E	6–20	Corrosion resistant layer	26, 27
Ti	S	—	—	12
Ti–W	MS	500–5 000 Å	Resistance films	—
V	E	0.086	—	30
W	S	500–5 000 Å	Barrier layer for ICs	28, 29

* ARE—Activated reactive evaporation.
E —Evaporation.
AE —Arc evaporation.
EG —Electron gun.
IBS —Ion beam sputtering.
IP —Ion plating.
MS —Magnetron sputtering.
RIS —Reactive ion sputtering.
RIP —Reactive ion plating.
RE —Reactive evaporation.
RAE—Reactive arc evaporation.
RSP—Reactive sputtering.
S —Sputtering.
SIP —Sputter ion plating.
TS —Triode sputtering.

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Table 35.2 CHEMICAL VAPOUR DEPOSITION OF ELEMENTS

Elements	*Process*	*Temp.* °C	*Thickness* μm	*Typical application*	*Ref.*
Al	Al R or Al HR_2 thermal decomp. (R usually isobutyl)	200–600	50	Impervious layer on plastics	6, 9
	$Al + AlX_3$ (X = halide)	700–1 000	20–100	Aluminizing steel and super alloys	10
	$AlCl_3 + H_2$	900–1 000			15
As	AsH_3 thermal decomp.	230–300	—	GaAlAs lasers	7
	AsH_3 plasma assisted				1
B	B_2H_6 thermal decomp.	400–700	—	B fibres	13
	BBr_3 thermal decomp.	1 000–1 300			
	$BBr_3 + H_2$	600–1 100		High purity boron	5
	$BCl_3 + H_2$ (also with laser excitation)	1 000–1 500	5–1 000	Jewelled bearings, fibres	2, 5, 12, 72
C (graphite)	CH_4, C_2H_6 thermal decomp.	2 000–2 500	500–3 000	Free-standing components	14
C (carbon)	CH_4, C_2H_6 thermal decomp.	900–1 200	1–50	Barrier layers, C–C composites	3, 4, 11
C (diamond and diamond-like carbon)	CH_4, C_3H_8 microwave plasma assisted	200–800	0.1–20	Anti-reflectance coating	70, 20
Co	$Co(acac)_2$* thermal decomp.	300–500	1.5	—	17
Cr	CrI_2 thermal decomp.	900–1 400	—	High purity chromium	19
	Cr dicumene	300–400	25–50	Coating nuclear fuel elements	14
	$Cr + NH_4Cl$ pack	950–1 050	20–50	Coating turbine blades	16
Cu	$Cu(acac)_2$* thermal decomp.	260–450	—	—	18

* acac = acetylacetonate.

Table 35.2 CHEMICAL VAPOUR DEPOSITION OF ELEMENTS—*continued*

Elements	*Process*	*Temp.* °C	*Thickness* μm	*Typical application*	*Ref.*
Ge	$GeCl_4 + H_2$	600	—	—	22
	GeH_4 thermal decomp.	400–900		Epitaxial semiconductor layer	21
Hf	HfX_4 thermal decomp. (X = I or Br)	—	—	—	25
Ir	$Ir(CO)_2Cl_2$ thermal decomp.	600	—	—	28
Mo	$MoX_5 + H_2$ (X = Cl, F)	650–1 400	8	Thin film resistors	26, 30
	$(Mo(CO)_6 + H_2$	300–600	0.2	Coating nuclear fuels	29
	$Mo(CO)_6$ plasma			Anti-reflection on surfaces for photochem. conversion	27, 24, 23
Nb	$NbCl_5 + H_2$	1 000–1 400	5–50	Nuclear fuel cladding	32
Ni	$Ni(CO)_4$ thermal decomp.	180–200	1–1 000	Vapour forming	33
	$Ni(acac)_2$* thermal decomp.	250–450		Coating of uranium	34, 38
	$Ni(CO)_4$ plasma assisted				24
	$Ni(CO)_4$ laser assisted		0.055	Localized deposit	31
Pb	$PbEt_4$ thermal decomp.	300–500	—	—	35
Pd	$Pd(acac)_2$* thermal decomp.	350–450	—	—	39
Pt	$Pt(CO)_2Cl_2$ thermal decomp.	600	—	—	46
	$Pt(acac)_2$* thermal decomp.	350–450			40
Re	$ReF_5 + H_2$	850–1 100	—	—	—
	$ReCl_5 + H_2$	600–1 200			42
	$ReOCl_4$ thermal decomp.	1 250–1 500			37
	$ReCl_5$ thermal decomp.	1 100–1 300		Thermionic emitters	41
Rh	$Rh(tfa)_3$† $+ H_2$	250	—	—	38
	$Rh(CO)_2Cl_2$ thermal decomp.	600			46
Ru	$Ru(CO)_5$ thermal decomp.	200	—	—	47
	$Ru(CO)_2Cl_2$ thermal decomp.	600			46
Sb	$SbCl_3$ thermal decomp.	500–600	—	—	49
	SbH_3 thermal decomp.	~150		Prod. of high purity Sb	48
Si	SiH_4 thermal decomp.	300–1 200	—	—	51, 71
	$SiCl_4 + H_2$	900–1 800		Prod. of polycryst. Si	
	$SiHCl_3 + H_2$	950–1 250	30	Solar cells	50
	SiH_4 plasma decomp.	300–1 150		Semiconductor layers	44
	Siliconizing Ni alloys			Corrosion-resistant layers on gas turbine parts	45, 43
Sn	Sn + NH_4Cl/MgO pack diffusion	450–750	10	Corrosion and wear resistant coating	53
Ta	$TaCl_5 + H_2$	900–1 100	5–20	Corrosion-resistant layers	54
				Thin film resistors	58
				Impregnation of C fibres	59
Ti	$TiBr_4$ thermal decomp.	1 100–1 400	—	Metal production	55
	TiI_4 thermal decomp.	1 200–1 500			56
U	UI_6 thermal decomp.	~1 500	—	—	57
V	$VCl_4 + H_2$	800–1 000	—	—	60
	VI_2	1 000–1 200	10–50		69, 61
W	$WF_6 + H_2$	400–700	1–1 000	Thin wall components	62
	$WCl_6 + H_2$	600–700	1–1 000	Erosion-resistant coatings on rocket motors	66, 63, 64
	$W(CO)_6$ thermal decomp.	350–600		Electron emission surfaces	67, 68
Zr	ZrI_4 thermal decomp.	1 000–1 500	5–50	Nuclear fuel cladding	65

* acac = acetylacetonate. † tfa = trifluoro-acetylacetonate.

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Table 35.3 PHYSICAL VAPOUR DEPOSITION OF OXIDES

Compound	*Process**	*Coating thickness* μm	*Typical applications*	*Ref.*
Al_2O_3	S	1–6	Passive sealing layers	—
	RSP		Wear-resistant layers	1, 2
	IP			
CuO/Cu_2O	r.f. S $Cu+O_2$	—	—	3
Cr_2O_3	r.f. S	0.1	Wear resistant layer	4, 5
	RE	0.01	Anti-reflectance coating	
NiO	S	1	—	6
SiO_2	MS	0.006	Mask layer on IC	—
	r.f. S	13	Multilayer laser fusion test	7, 8
SiO–Cr	r.f. S	—	Resistor film	9
SnO_2	RSP	—	Transparent electrodes for electro-optics	10
Ta_2O_5	r.f. S $Ta+O_2$	—	Optical wave guides	11
TiO_2	RSP $Ti+O_2$	1–2	Anti-reflectance coatings on Al mirror	12
ZnO	r.f. S	—	Surface acoustic wave (SAW) devices	13
ZrO_2	d.c./r.f. S	25–100	Thermal barrier coatings for gas-turbine parts	14
(Y-stabilized)	EB			15

* *See* Table 35.1 for the key.

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Table 35.4 CHEMICAL VAPOUR DEPOSITION OF OXIDES

Material	*Process*	*Temp.* °C	*Coating thickness* μm	*Typical applications*	*Ref.*
Al_2O_3	$AlCl_3+CO_2+H_2$	850–1 800	2–8	Hard coating for tool tips Coating for nuclear fuels	1–5
	$AlCl_3+O_2$ plasma assisted	230–350		Passive sealing layer for integrated circuits. Single crystal growth	
	$Al(CH_3)_3$ or $Al(OC_3H_7)_3+O_2$	275–500			
B_2O_3–SiO_2	$B_2H_6+SiH_4+O_2$	350	0.4–0.6	Diffusion source for doping electronic materials. Cladding for optical fibres	23
Cr_2O_3	$Cr(CO)_6+O_2$	400–600	<25	Oxidation-resistant coating	6
Fe_2O_3	$Fe(acac)_3+O_2$ plasma assisted	400–600	—	—	24
SiO_2	SiH_4+O_2 (+$h\nu$)	300–430	5–25	Passive layer-encapsulant for electronics	7–12
	$Si(OEt)_4$ thermal decomp.	800–1 000		Anti-reflectance coating	25
	$Si(OEt)_4+H_2O$	500–1 000		Corrosion-resistant coating for chemical plant. AGR plant	
	SiH_4+N_2O	300–1 500			
	$SiCl_4+O_2$ plasma assisted	>1 000	20–50	Prep. of optical fibres	
SnO_2	$SnCl_4+O_2$	600–1 000	0.1	Semiconductor assemblies. Optoelectronic applications.	13–15
	$SnCl_4+H_2O$	>430		Transparent electrically conducting coatings	
	$Sn(CH_3)_4+O_2$	400–600	0.1		
TiO_2	$TiCl_4+O_2$ + hydrocarbon (in flame)	450–800	—	Pigment production	16–19
	$TiCl_4+CO$ plasma assisted or $TiCl_4+O_2$ plasma assisted			Dielectric films in MOS structure	
	$Ti(OC_3H_7)_4+O_2$	450			26
$YBa_2Cu_3O_{7-x}$	$Y/Ba/Cu(acac)+O_2$	400–600	1–20	Superconductor with high T_c	27, 28
ZrO_2	$Zr(acac)_4+O_2$	450–700	—	MOS devices	20–22
	$ZrCl_4+CO_2+CO+H_2$	1 000	5–10	Hard coatings on sintered carbides. Oxidation-resistant coatings	
	$Zr(OC_3H_7)_4$	500–600	12–75		

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Table 35.5 PHYSICAL VAPOUR DEPOSITION OF NITRIDES

Compound	*Process**	*Coating thickness* μm	*Typical applications*	*Ref.*
AlN	RIS $Al+N_2$	—	Electronic material.	1–3
	RIP $Al+N_2$ or NH_3—substrate 1 000°C	2	Refractory dielectric. Acoustic transducers.	
	RE $Al+NH_3$	0.6–1.5	SAW diodes	
HfN	RSP	—	Thin film dielectrics	4
	RIP $Hf+N_2$	0.2–0.3		
NbN	RSP	—	Superconducting layers	5
TaN	RSP	115 Å min^{-1}	Resistor film	6
Si_3N_4	RIS $Si+N_2$	0.25–0.08	Encapsulant for GaAs	1,
	r.f. RSP $Si+N_2$		Optical wave guides	7–9
	RSP $Si_3N_4+N_2$			
TiN	RSP $Ti+N_2$	—	Hard coatings on steel tools	10–11
	ARE $Ti+N_2$	5–15		
	RAE $Ti+N_2$			
W_2N	RSP	100 Å min^{-1}	Superconductivity	6

* *See* Table 35.1 for key.

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Table 35.6 CHEMICAL VAPOUR DEPOSITION OF NITRIDES

Material	*Process*	*Temp.* °C	*Coating thickness* μm	*Typical applications*	*Ref.*
AlN	$AlCl_3 + NH_3 + H_2$	800–1 000	0.5	Electronic applications Refractory dielectrics SAW devices	1–5
	$Al + N_2$	1 800–2 000	Whiskers	High strength refractories	
	$AlCl_3 + N_2 + H_2$ plasma assisted	800–1 200		III/V semiconductors	
	$(CH_3)_3Al + NH_3 + H_2$	1 200	Epitaxial		
BN	$BCl_3 + NH_3$	1 000–2 000	1–2 000	Formation of free-standing crucibles, tubes and plates	6–12
	$BF_3 + NH_3$	1 000–2 000		Travelling wave tube isolators Insulating layers in semi-cond. manufacture	
	$B_2H_6 + NH_3$ plasma assisted	400–700	0.2–0.6	Diffusion doping of Si	
	$B_2H_6 + N_2$ microwave plasma assisted	800	4	Cubic BN for wear resistance	24
HfN	$HfCl_n + N_2 + H_2$ $(n = 2, 3, 4)$	900–1 300	5–10	Wear-resistant coatings. Diffusion barriers	13
TaN	$TaCl_5/TaBr_5 + N_2$	800–1 500	—	Resistor film	14–15
Si_3N_4	$SiH_4 + N_2/NH_3$ plasma assisted	350	0.15	Encapsulation of III/V semiconductor devices	
	$SiF_4 + NH_3$	1 000–1 500		Anti-reflection coatings on solar cells	12, 16–20
	$SiCl_4 + NH_3$	1 000–1 500	10–2 000		
	$SiHCl_3 + NH_3$	1 100–1 400		Gas turbine parts	
	$SiH_4 + NH_3 + N_2H_4$ chem. decomp.				
TiN	$TiCl_4 + N_2 + H_2$	650–1 700	2–8	Hard coatings for hard-metal cutting tools. Scratch-resistant decorative surfaces. Diffusion barrier layers	21–23, 25
	$Ti(NMe_2)_4$ thermal decomp.	300–500			
	$TiCl_4 + N_2 + H_2$ plasma assisted	< 550			
ZrN	$ZrCl_4 + N_2 + H_2$	900–1 200	2–8	Hard coatings for cutting tools	13

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Table 35.7 PHYSICAL VAPOUR DEPOSITION OF CARBIDES

Compound	*Process**	*Coating thickness* μm	*Typical applications*	*Ref.*
Cr_3C_2	RSP IP	0.3–2.5	Solar energy collectors Wear-resistant coatings	1–2
Cr_7C_3	ARE			
HfC	ARE/RE $Ar+C_2H_2+Hf$	2.5 μm min^{-1}	—	2
Mo_2C	RSP IP $Ar+CH_4$	0.18	Solar energy absorption	1
NbC	ARE/RE $Ar+CH_4$ or C_2H_4+Nb	2.5 μm min^{-1}	Optical/semiconductor	2
SiC	RSP $Ar+C_2H_2$	1	Electronic barrier coating	3–4
Ta_2C	RSP	0.8	Solar energy absorption	1, 2
TaC	$Ar+CH_4$, C_2H_2 ARE/RE $Ta+C_2H_2$	— 1.5 μm min^{-1} at 590°C	—	— 5
TiC	RSP $A+CH_4$ ARE ARE/RE $Ti+C_2H_4$	5.0 μm at 700/ 900°C 4.0 μm min^{-1} at 450°C	Cutting tools Wear-resistant surfaces	2 6, 7, 8
VC	ARE $V+C_2H_2$	3.0 μm min^{-1} at 555°C	—	2
W_2C	RSP SIP W/C	0.8	Solar energy absorption Drill tips, pump components	1 10
WC	$W+Ar+CH_4$	—	—	—
ZrC	ARE/RE $Zr+C_2H_2$	5.0 μm min^{-1} at 540°C	Diffusion barrier	2, 9

* *See* Table 35.1 for key.

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Table 35.8 CHEMICAL VAPOUR DEPOSITION OF CARBIDES

Material	*Process*	*Temp.* °C	*Coating thickness* μm	*Typical application*	*Ref.*
B_4C	BCl_3+CO+H_2	1 200–1 800		Nuclear industry Armament Abrasive blasting nozzles Rocket nozzles Fibres	1–6
	$B_{10}C_2H_{12}$ thermal decomp.	1 000–1 300			
	$B_2H_6+CH_4$				
	BMe_3 thermal decomp.	~550			
	BCl_3+CCl_4 thermal decomp.	1 200–2 000			
	$BCl_3+CH_4+H_2$	1 300–1 900	10–1 000		
Cr_3C_2	$Cr(CO)_6+H_2$	300–650			7
Cr_7C_3	$CrCl_2+CH_4+H_2$	~1 000	10–40	Wear-resistant coatings HV 2250	8
	$CrCl_2+H_2$	1 000		Chromizing of steel	9
	Cr dicumene – thermal decomp.	450–650			10
HfC	$HfCl_4+H_2+CH_4$	1 000–1 500	5	Diffusion barrier Wear resistant coating	11 12
Mo_2C	$Mo(CO)_6$ thermal decomp.	350–475	—	Wear-resistant layer	13
	$MoF_6+C_6H_6+H_2$	400–1 000			14
NbC	$NbCl_5+CCl_4+H_2$	1 500–1 900	—	Wear-resistant coating Diffusion barrier	15
SiC	$SiCl_4+CH_4$	1 000–2 000	10–1 000	Oxidation-resistant coatings. Single fibres of high strength	16
	$CH_3SiCl_3+H_2$	1 000–1 600		Heating elements. Electrical heat stylus	17
	$SiH_4+C_2H_4$ or CH_4 plasma assisted		~1	Electrochemical machining tool	18
Ta_2C TaC	$TaCl_5+CH_4$	1 100		Coating W filaments for incorporation into superalloy matrices	19
TiC	$TiCl_4+H_2+CH_4$ or C_6H_6	800–1 400	2–12	Wear-resistant coatings on steel and carbides—particularly cutting tools	20–24
	$TiCl_4+CCl_4+H_2$	>1 000			35
	Ti organic	150–500			36
VC	$VCl_2+CH_4+H_2$	1 050–1 130	—	Wear-resistant coating	25–26
	Diffusion coating VC_x ($x=0.84$–0.89)				
WC	$WF_6+C_6H_6+H_2$	400–900	—	Wear-resistant coatings	27–31
W_2C	$W(CO)_6$ thermal decomp.	300–500	5–50		
	WF_6+CO+H_2	600–1 000			
	$WCl_6+CH_4+H_2$	900–1 150			
ZrC	$ZrCl_4+CH_4+H_2$	1 050–1 500	50–100	Wear-resistant coating. Diffusion barrier layer	32–33
	$ZrCl_4+C_3H_6+H_2$	1 150–1 300	50	High temperature insulation. Nuclear fuel coating	34

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36 Superplasticity

Superplasticity is the name given to the ability of a material to sustain extremely large deformations at low flow stresses at a temperature around half the melting point expressed in Kelvin. It is only found in metals and alloys, which have, and can maintain during forming, a very fine grain structure. A parameter which indicates the degree of superplasticity is the strain rate sensitivity m, given by the high temperature flow equation: $\sigma = K\dot{\varepsilon}^m$, σ is the stress for plastic flow, $\dot{\varepsilon}$ the applied strain rate and K is a constant. Superplastic materials have m values normally between 0.4 and 0.6, while most other metals and alloys at elevated temperatures have m values of 0.2; viscous materials (e.g. glass) behave like a Newtonian fluid and have m values of 1.

A full discussion of the mechanism of superplasticity, including methods for determining m, can be found in K. A. Padmanabhan and G. J. Davies, 'Superplasticity', Berlin, Springer-Verlag, 1980.

The tables in this chapter give alloy systems with the temperature range over which they show superplasticity, the maximum possible percentage elongation, and the m value. Table 36.1 gives mainly non-ferrous systems, Table 36.2 iron and steel systems, and Table 36.3 powdered materials with superplastic properties. The values of about 10^{-4} quoted under remarks are preferred strain rates.

Table 36.1 NON-FERROUS SYSTEMS SHOWING SUPERPLASTICITY

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*References*	*Remarks*
Ag–28.1Cu	675	500	0.53	1	
Al (commercial)	380–580	6000	0.2	2	
Al–7.6Ca	400–600	850	0.78	3	Euratom alloy
Al–7.6Ca	~500	570	0.32	69	Optimum 500°C at 4.16×10^{-4}
Al–5Ca–5Zn	450			4	Alcan 08050
Al–17Cu	400–520	600	0.35	5	
Al–32.74Cu	~510	>160	0.7	66	After 25% pre-deformation at 510°C
Al–33Cu	380–520	1150	0.9	6	
Al–6Cu–0.5Zr	400–500	2000	0.5	7	TI Supral
Al–2.59Cu–2.26Li–0.16Zr(2090)	450–480	1800	—	64	Optimum 520°C at 5×10^{-4}
Al–4.40Cu–0.70Mg–0.80Si–0.75Mn(2014)+15%SiC	450–480	160	0.4	65	Elong% 350% at 5.25 MPa hydrostatic pressure
Al–25–33Cu–7–11Mg	420–480	>600	0.72	8	
Al–Ga–Ti	RT	—	0.3–0.5	9	
Al–4Ge	400–500	230	—	10	
Al–2.4Li–2.0Cu–0.70Mg–0.08Zr(8091	490–550	1350	0.6	61	Optimum 530°C at 10^{-3}–10^{-4}
Al–2.5Li–1.2Cu–0.6Mg–0.1Zr(8090)	520–530	660–1200	0.65	62	2–3 mm sheet at $2–5 \times 10^{-4}$
Al–2.4Li–1.2Cu–0.60Mg–0.12Zr(8090)	~530	>1000	0.68	63	2 mm sheet at 5×10^{-4} and 5–10 micron grain size
Al–1.56Mg–5.6Zn	530	500	0.7	11	
Al–3Mg–6Zn	340–360	400	0.35	12	TI BA 480
Al–0.93Mg–10.72Zn–0.42Zr	550	1550	0.9	11	

Table 36.1 NON-FERROUS SYSTEMS SHOWING SUPERPLASTICITY—*continued.*

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*References*	*Remarks*
Al–5.8Mg–0.37Zr + others	520	> 800	0.6	13	
Al–4.89Mg–1.19Cr	482–520	> 1 000		67	Optimum 520°C at 1.6×10^{-2}
Al–8.0Mg–1.0Li–0.15Zr	300	> 1 000			
Al–5.70Zn–2.30Mg–1.50Cu–0.22Cr(7475) + 15%SiC	495–515	97	0.43	65	Elong% 310% at 5.25 MPa hydrostatic pressure
Al–5.70Zn–2.30Mg–1.50Cu–0.22Cr(7475)	~530	1 300		68	Optimum 530°C at 2.8×10^{-4}
Be	600–700	130	0.9	14	
Bi–44.5Pb	20	600	0.42	15	
Bi–31Pb–17Sn	20	600	0.45	15	
Bi–43Sn	20	1 950	—	15	
Cd–17.5Zn	20	400	0.5	16	
Cd–27Zn	20–30	350	0.5	16	
Co–10Al	1 200	450	0.47	17	
Cr–30Co	1 200	160	—	18	
Cu–9.8Al	540–700	700	0.7	19	
Cu–9.5Al–14Fe	800	> 800	0.7	19	CDA619
Cu–10Al–3Fe	800	7 200.6	0.6	20	
Cu–10Al–4Fe	750	1 000	0.6	21	
Cu–2.8Al–1.8Si–0.4Co	500–600	320	0.5	22	CDA 638
Cu–10–20Mg	700	250	-	23	
Cu–7P	410–600	> 600	0.5	24	Solder, temporary superplasticity
Cu	450	> 300	0.45	25	IN836
Cu–9.8Zn	163	570	0.4–0.5	26	
Cu–40Zn	627	> 525	0.75	27	
Cu–48Zn	500–800	450	0.9	28	
Cu–38.5Zn–3Fe	500–800	330	0.53	25	
Cu–38Zn–15Ni–0.2Mn	450–565	200	—	29	
In–34Bi	20	450	0.76	30	Eutectic
Mg–33Al	350–400	2 100	0.8	31	Eutectic
Mg–9Li	180	460	0.52	70	At 3×10^{-4}; 6.1 micron grain size
Mg–9Li	200	445	0.47	70	At 1×10^{-3}; 7.1 micron grain size
Mg–9Li	250	310	0.44	70	At 1×10^{-4}; 14.2 micron grain size
Mg–4.3Al–3Zn–0.5Mn				32	Russian MA 15
Mg–30.7Cd	450	250	—	23	
Mg–5.5Zn–0.5Zr	270–310	1 000	0.6	33	ZK 60
Mg–0.5Zr	500	150	0.3	34	
Ni	800	180	0.5	35	
Nichrome*	1 000	190	0.5	35	
Ni–20Cr	800–900	200	—	36	
Ni–15Co–9.5Cr–5.5Al–5Ti–3Mo	810–1 070	1 000	0.5	37	IN 100
Ni–34.9Cr–26.2Fe–0.58Ti	795–855	> 1 000	0.5	38	
Ni–38Cr–14Fe–1.75Ti–1Al	810–980	1 000	0.5	38	
Ni–39Cr–10Fe–1.75Ti–1Al	810–980	1 000	0.5	38	
Ni–16Cr–8.3Co–3.4Ti–3.4Al–2.6W–1.78Ta–1.75Mo 0.9Nb–0.1Zr–0.17C–0.01B	800–1 000	500	0.4	39	IN 738
Pb–5Cd	20	--	0.35	40	
Pb–17.4Cd	25–100	> 350	0.6	41	Eutectic
Pb–30Cd	25	> 900	0.35	41	
Pb–40In	55	215	—	42	
Pb–11Sb	246	1 200	—	43	Eutectic
Pb–19Sn	20–80	—	0.5	44	
Pb–7.9Tl	20	400	0.5	45	

* Registered Trade Mark.

Table 36.1 NON-FERROUS SYSTEMS SHOWING SUPERPLASTICITY—*continued*

Alloy system	*Temperature range °C*	*Maximum elongation %*	*m*	*References*	*Remarks*
Sn	20	--	0.5	44	
Sn–1Bi	22	500	0.48	46	
Sn–5Bi	20	1 000	0.68	47	
Sn–5Cc	25	350	0.32	48	
Sn–2Pb	20–80	600	0.5	44	
Sn–38Pb	20–170	> 4 850	0.7	44	Eutectic
Sn–32Pb–18Cd	25–70	—	0.55	49	
Sn–31.1Pb–3.4Zn	25–70	500	0.55	49	
Sn–2–6Sb	140–210	—	0.4	50	
Sn–9 8Zn	20–180	570	0.5	26	Eutectic
Ti (commercial)	900	—	0.8	37	RC 70
Ti–4Al–0.25O_2	950–1 050	—	0.6	37	
Ti–5Al–2.5Sn	900–1 100	450	0.72	37	
Ti–6Al–4V	750–1 000	1 000	0.85	37	Commercial alloy used throughout world
Ti–6Al–5Zr–4Mo–1Cu–0.25Si	800	300	—	23	IMI 700
Ti–8Mn	580–900	140	0.95	28	
Ti–15Mo	580–900	450	0.6	28	
Ti–11Sn–5Zr–2.25Al–1Mo–0.25Si	800	500	--	23	IMI 679
Zn (Commercial)	20 - 70	409	0.2	51	
Zn–0.2Al	23	465	0.8	52	
Zn–0.4Al	20	650	0.5	51	
Zn–4.9Al	200–360	300	0.68	53	Eutectic
Zn–18Al	22–350	—	0.6	54	
Zn–22Al	20–300	2 900	0.7	54	Eutectoid; main commercial alloy, i.e. SPZ
Zn 36Al	22 350	—	0.5	54	
Zn 40Al	250–300	1 300	0.65	55	
Zn 50Al	250–300	1 000	0.3	55	
Zn–22Al–0.1Cu	250	—	0.65	56	
Zn–22Al–4Cu	20–250	1000	0.5	57	
Zn–22Al–0.2Mn	20–250	1000	0.5	57	
Zn–0.1Ni–0.04Mg	100–250	> 980	0.51	58	
Zr–2.5Nb	627–827	430	0.6	59	
Zr–1.2–1.7Sn–0.07–0.2Fe–0.05–0.15Cr–0.03–0.08Ni	800–1 050	2 500	0.57	60	Zircaloy 2 + O_2
Zr–1.2–1.7Sn–0.12–0.18Fe0.05–0.15Cr–0.007N;	800–1 050	2 500	0.57	60	Zircaloy 4 + O_2
W–15–30Re	2000	260	0.8	17	

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Table 36.2 IRON AND STEEL SYSTEMS SHOWING SUPERPLASTICITY

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*References*	*Remarks*
Cast iron					
Fe–2.13C–1.41Mn	650	526	0.5	1	White
Fe–2.36C–1.48Mn	650	291	0.5	1	White
C. steels					
Fe–0.1C	827	—	0.9	2	

Table 36.2 IRON AND STEEL SYSTEMS SHOWING SUPERPLASTICITY—*continued*

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*References*	*Remarks*
Fe–0.4C	827	—	0.6	2	
Fe–0.9C	1 000	>300	—	16	At 2.5×10^{-4}
Fe–0.8C	750–860	100	0.35	3	
Fe–1.3C	540–650	500	0.4	4	
Fe–1.3C	630	700	—	16	At 1.3×10^{-4}
Fe–1.6C	540–650	500	0.45	4	
Fe–1.6C	630	760	—	16	At 1.3×10^{-4}
Fe–1.9C	540–650	500	0.5	4	
Fe–1.9C	650	380	—	16	At 1.7×10^{-4}
Alloy steels					
Fe–0.3C–2Al	1 040	—	0.37	5	
Fe–0.34C–2Al–0.47Mn	900–950	372	0.48	6	
Fe–1.6C–1.5Cr	650	1 220	—	7	AISI 52160
Fe–0.14C–1.93Mn	727–800	—	0.6	2	
Fe–0.44C–2Mn	700–800	460	0.8	2	AISI 340
Fe–2C–30Mn	770–950	250	—	8	
Fe–C–Mn steels + V, Nb, Al and Ti	800–1 000	184	0.7	9	
Fe–0.8C–1.1Mn–0.04Nb–1.5Ti	1 000	184	—	16	At 1.7×10^{-4}
Fe–0.15C–1.2Mn–0.04Nb	790	738	—	16	At 1.7×10^{-4}
Fe–0.15C–1.3Mn–0.3Si	780	640	—	16	At 1.7×10^{-4}
Fe–0.2C–0.6Mn–0.2Si–1Cr	770	600	—	16	At 1.7×10^{-4}
Fe–0.3C–0.6Mn–0.2Si–1Cr	740	500	—	16	At 1.7×10^{-4}
Fe–0.2C–0.8Mn–0.3Si–1Cr	760	845	—	16	At 1.7×10^{-4}
Fe–0.9C–1.2Mn–0.5Cr–0.5W–0.5V	650	1 200	—	16	At 1.6×10^{-4}
Fe–0.75C–0.3Mn–1.3Cr	650	840	—	16	At 2.5×10^{-4}
Fe–1.2C–0.3Mn	700	780	—	16	At 0.7×10^{-4}
Fe–1C–1.5Si–32Mn–11Al	800	>500	—	16	At 0.7×10^{-3}
Fe–0.07C–0.91Mn–0.5P–0.1V	800–950	169	0.31	6	
Fe–0.14C–1.16Mn–0.5P–0.11V	800–950	270	0.57	6	
Fe–0.16C–1.54Mn–1.98P–0.13V	900	376	0.55	6	
Fe–0.18C–1.54Mn–0.9P–0.11V	900	320	0.55	6	
Fe–0.42C–1.87Mn–0.24Si	727	460	0.65	2	AISI 1340
Fe–0.91C–0.45Mn–0.12Si	710–915	142	0.42	10	
Fe–0.13C–1.11Mn–0.11V	700–900	310	0.45	6	
Fe–0.03–0.1C–3.9Ni–3Mo–1.58Ti	850–1 000	820	0.67	11	
Fe–0.01C–6.4Ni–0.35Nb	700–800	—	0.4	12	
Fe–0.2C–3.1Ni–0.29Nb	700–800	—	0.56	12	
Fe–0.12C–1.97Si	800–950	150	0.26	6	
Fe–1.5Cr–1P	800	400	—	16	At $\sim 10^{-4}$
Stainless steels					
Fe–13Cr–16Mn	750	228	—	16	At 0.4×10^{-3}
Fe–C–12Cr–10Ni + Ti	900–950	—	—	13	Martensitic Russian Kh12Ni 10T
Fe–C–12Cr–10Ni + Ti + Al	900–950	—	—	13	Martensitic Russian Kh12Ni10TYu
Fe–C–13Cr–7Ni	900–950	—	—	13	Martensitic Russian OKh13N7
Fe–0.08C–20Cr–9Ni–7Mn + Ti	990–1 020	195	0.3–0.5	14	Russian O8Kh20N9G7T
Fe–20Cr–10Ni–0.7N	1 000	270	—	16	At 0.8×10^{-3}
Fe–20Cr–10Ni–0.7N	800	527	—	16	At 0.8×10^{-3}
Fe–25Cr–6.5Ni–0.6Ti	927	500	—	16	At 2.6×10^{-3}
Fe–30Cr–5.0Ni–0.6Ti	927	200	—	16	At 2.6×10^{-3}
Fe–34Cr–10Ni–0.6Ti	982	460	—	16	At 2.6×10^{-3}
Fe–28Cr–19Ni–0.6Ti	982	260	—	16	At 2.6×10^{-3}
Fe–28Cr–22Ni–0.6Ti	982	160	—	16	At 2.6×10^{-3}
Fe–36Cr–26Ni–0.6Ti	982	520	—	16	At 2.6×10^{-3}
Fe–41Cr–22.5Ni–0.6Ti	982	>1 000	—	16	At 2.6×10^{-3}
Fe–46Cr–16Ni–0.6Ti	982	480	—	16	At 2.6×10^{-3}
Fe–43Cr–33Ni–0.6Ti	982	>740	—	16	At 2.6×10^{-3}
Fe–55Cr–35Ni–0.6Ti	982	400	—	16	At 2.6×10^{-3}
Fe–39Cr–52Ni–0.6Ti	982	740	—	16	At 2.6×10^{-3}

Table 36.2 IRON AND STEEL SYSTEMS SHOWING SUPERPLASTICITY—*continued*

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*References*	*Remarks*
Fe–39Cr–49Ni–2Ti–1Al	982	> 1 000	—	16	At 2.6×10^{-3}
Fe–45Cr–55Ni–0.6Ti	982	720	—	16	At 2.6×10^{-3}
Fe–25Cr–5.7Ni–0.7Ti–0.1Al	927	600	—	16	At 4.4×10^{-3}
Fe–30Cr–6Ni–0.7Ti–0.16Al	871	300	—	16	At 4.4×10^{-3}
Fe–26Cr–6.5Ni–0.4Ti	960	1 050	–	16	At 3.2×10^{-4}
Fe–25Cr–7Ni–3Mo–0.14N	950	2 500	—	16	At 2×10^{-3}
	1 050	> 2 000			
Fe–26Cr–6.5Ni–3Mo–0.12N	1 000	> 3 000	—	16	At 4×10^{-3}
Fe–18Cr–4Ni–3Si–3Mn–1Cu	1 000	765	—	16	
Fe–18.5Cr–4Ni–1.7Si–3.2Mn–1Cu	950	750	—	16	At 2×10^{-3}
Fe–24.8Cr–6.4Ni–3Mo–0.12N	1 000	> 1 000	—	16	At 8×10^{-3}
Fe–C–26Cr–6.5Ni	700–1 020	> 1 000	0.62	15	IN 744

Table 36.3 POWDERED MATERIAL SYSTEMS SHOWING SUPERPLASTICITY

Alloy system	*Temperature range* °C	*Maximum elongation* %	*m*	*References*	*Remarks*
Al–4.89Mg–1.19Cr	482–520	> 1 000	—	18	Optimum 520°C at 1.6×10^{-2}
Fe–3C–1.5Cr	700	1 410	—	16	At 1.7×10^{-4}
Fe–3C	700	940	—	16	At 1.7×10^{-4}
Fe–2.4C	700	480	—	16	At 1.7×10^{-4}
Fe–23.4Cr–5Ni–1.5Mo–1Cu–0.15N	1 070	500	—	16	At 2×10^{-4}; RS ribbon/hot ext.
Fe–26Cr–6.5Ni–3Mo–0.11N	950	> 1 000	—	16	At 1.7×10^{-3}; RS ribbon/hot ext.
Fe–21Al–4B	871	281	—	16	
Fe–50Cu	800	300	—	16	At $\sim 10^{-4}$
Ni–0.125C–6Al–6Cr–4Mo–2.5Nb–8Ta–4W	980	> 600	—	17	NASA-TAZ-8a
Ni–0.15C–18.5Co–15Cr–4.2Al–5.2Mo–3.5Ti	1 020	1 000	0.42	17	U700
Ni–5.4Al–0.015B–0.14C–7.5Co–6Cr–2Mo–0.5Nb–9Ta–1Ti–6W–Hf–Re–Zr	1 090	> 300	—	17	NASA-TRW-VIA
Ni–5.5–6.5Al–1.8–2.8Nb–12–14Cr–3.8–5.2Mo up to 2.5Fe–0.5–1Ti	1 090	230	—	17	IN 713

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37 Metal–matrix composites

Metal-matrix composites are engineered materials comprising reinforceants of high elastic modulus and high strength in a matrix of a more ductile and tougher metal of lower elastic modulus and strength. The metal–matrix composite has a better combination of properties than can be achieved by either component material by itself. The objective of adding the reinforceant is to transfer the load from the matrix to the reinforceant so that the strength and elastic modulus of the composite are increased in proportion to the strength, modulus and volume fraction of the added material.

The reinforcement can take one of several forms. The least expensive and most readily available on the market are the particulates. These can be round but are usually irregular particles of ceramics, of which SiC and Al_2O_3 are most frequently used. Composites reinforced by particulates are isotropic in properties but do not make best use of the reinforceant. Fine fibres are much more effective though usually more costly to use. Most effective in load transfer are long parallel continuous fibres. Somewhat less effective are short parallel fibres. Long fibres give high axial strength and stiffness, low coefficients of thermal expansion and, in appropriate matrices, high creep strength. These properties are very anisotropic and the composites can be weak and brittle in directions normal to that of the fibres. Where high two-dimensional properties are needed, cross-ply or interwoven fibres can be used. Short or long randomly oriented fibres provide lower efficiencies in strengthening (but are still more effective than particulates). These are most frequently available as SiC whiskers or as short random alumina ('Saffil') fibres or alumino-silicate matts.

Long continuous fibres include drawn metallic wires, mono-filaments deposited by CVD or multi-filaments made by pyrolysis of polymers. The properties of some typical fibres are compared in Table 37.1. The relative prices are given as a very approximate guide.

Because most composites are engineered materials, the matrix and the reinforceant are not in thermodynamic equilibrium and so at a high enough temperature, reaction will occur between them which can degrade the properties of the fibre in particular and reduce strength and more especially fatigue resistance. As many composites are manufactured by infiltration of the liquid metal matrix into the pack of fibres, reaction may occur at this stage. Some typical examples of interaction are listed in Table 37.2.

In order to obtain load transfer in service, it is essential to ensure that the reinforceant is fully wetted by the matrix during manufacture. In many cases, this requires that the fibre is coated with a thin interlayer which is compatible with both fibre and matrix. In many cases, this also has the advantage of preventing deleterious inter-diffusion between the two component materials. The data on most coatings are proprietary knowledge. However, it is well known that silicon carbide is used as an interlayer on boron and on carbon fibres to aid wetting by aluminium alloys.

The routes for manufacturing composites are still being developed but the most successful and lowest cost so far is by mixing particulates in molten metal and casting to either foundry ingot or as billets for extrusion or rolling. This is applied commercially to aluminium alloy composites. Another practicable route is co-spraying in which SiC particles are injected into an atomized stream of aluminium alloy and both are collected on a substrate as a co-deposited billet which can then be processed conventionally. This is a development of the Osprey process and can be applied more widely to aluminium and other alloys. Other routes involve the infiltration of molten metal into fibre pre-forms of the required shape often contained within a mould to ensure the correct final shape. This can be done by squeeze casting or by infiltrating semi-solid alloys to minimize interaction between the fibre and metal. Fibres can also be drawn through a melt to coat them and then be consolidated by hot-pressing.

To reduce interaction, solid state methods can be used, e.g. cold isostatic pressing (CIP) and

Table 37.1 PROPERTIES OF REINFORCING FIBRES AT ROOM TEMPERATURE (BASED ON REFERENCE 9)

Fibre	*Form*	*Preparation route*	*Diameter* μm	*Density* $g cm^{-3}$	*Fracture stress* MPa	*Elastic modulus* GPa	*Coefficient of thermal expansion* $K^{-1} \times 10^{6}$	*Price relative to glass fibre*
Tungsten	Wire	Drawn	10–500	19.2	2500	400	5.0	1000–50
Steel	Wire	Drawn	10–250	7.8	2500	210	15.0	30–1
Boron	Cont. mono-filament	Chemical vapour depos.	150	2.6	3500	400	8.0	250
SiC	Cont. mono-filament	Chemical vapour depos.	150	3.4	3800	450	4.5	500
SiC	Cont. multi-filament	Polymer fibre pyrolysis	10–15	2.6	2500	200	4.5	100
SiC	Whisker (random, short)	Polymer fibre pyrolysis	0.1–2.0	3.2	10000	700	4.5	150
~Al_2O_3	Multi-filament	Oxide/salt fibre	15–25	3.9	1500	380	7.0	100
~Al_2O_3	Random short fibres	pyrolysis	2–4	3.5	2000	300	7.0	25
C(high modulus)	Cont. multi-filament	Polymer fibre pyrolysis	10	2.0	3000	600	0	1000
C(med. strength)	Cont. multi-filament	Polymer fibre pyrolysis	8	1.9	4200	300	0	100
Alumino-silicate Glass(27% SiO_2)	Random short fibres	Polymer fibre pyrolysis	3	3.0	850	150	..	20
Alumino-silicate Glass(47% SiO_2)	Random short fibres	Drawn from melt	3	2.7	1750	105	–	1
S-Glass	Cont. multi-filament	Drawn from melt	3–20	2.5	4000	90	3.0	2.5

Table 37.2 TYPICAL INTERACTIONS IN SOME FIBRE MATRIX SYSTEMS

System	*Potential interaction*	*Temperature of significant interaction* °C	*References*
Al–C	Formation of Al_4C_3 at interface. Degradation of C fibre properties.	550 ~495	9
Al–Al_2O_3	No significant reaction at normal fabrication temperatures		9
Al–oxide ($Al_2O_3 \cdot SiO_2$ B_2O_3)	B_2O_3 reacts with Al to form borides.	770	10
Al–B	Boride formation: interlayer of SiC needed.	500	9
Al/Li–Al_2O_3	Interfacial layer of $LiAl_5O_8$ on liquid infiltration.	~650	13
Al–SiC	No significant reaction below melting point. Al_4C_3 and Si can form in liquid Al.	m.p. 660 >700	9 12
Al–steel	Formation of iron aluminides.	500	9
Co–TaC	Directionally solidified eutectic: dissolution and re-precipitation.	1200	9
Cu–W	No interaction up to melting point.	1083	9
Fe–W	Formation of Fe_7W_6: dissolution of fibre.	1000	9
Mg(AZ91)–C	No significant reaction at m.p. of alloy provided O and N avoided during infiltration.		11, 14
Ni–Al_2O_3	Slight reaction to pit fibre. $NiAl_2O_4$ spinel forms in air.	1100 1100	9
Ni–C(I)	Ni activates recrystallization of fibre.	1150–1300	9
Ni–(II)	Ni activates recrystallization of fibre.	800	9
Ni–SiC	Formation of nickel silicides.	800	9
Ni–W	Recrystallization of fibre. Degradation of creep properties.	1000 900	9
Ti–B	Formation of TiB_2.	750	9
Ti–SiC	Formation of TiC, $TiSi_2$ and Ti_5Si_3.	700	9

sintering or hot isostatic pressing (HIP) of metal powders mixed with short fibres. Diffusion-bonding laminates of layers of fibres and metal foil is also effective.

The properties which can be achieved in composites include higher strength, higher stiffness, improved high-temperature properties, lower or matched coefficients of thermal expansion and improved wear resistance. This is usually at the expense of conventional ductility but in most cases improved fracture toughness can be obtained. The following tables illustrate what has been achieved in aluminium, magnesium, titanium and zinc alloys. The improvement in strength is often larger in the weaker alloys with less benefit being realized in the stronger alloys, e.g. see Table 37.3. All alloys show an improvement in elastic modulus when reinforced.

Table 37.3 MECHANICAL PROPERTIES OF ALUMINIUM ALLOY COMPOSITES AT ROOM TEMPERATURE

Base Alloy	*Nominal composition*	*Form*	*Heat treatment*	*% particulate*	*0.2% proof stress* MPa	*Tensile stress* MPa	*Elongation* %	*Elastic modulus* GPa	*Fracture toughness* MPa $m^{-1/2}$	*Density* g cm^{-3}	*References*
6061	Mg 1.0	Extrusion	T6	Nil	276	310	20.0	69.9	29.7	2.71	1,2
	Si 0.6			10% Al_2O_3	297	338	7.6	81.4	24.1	2.81	1,2
	Cu 0.2			15% Al_2O_3	317	359	5.4	87.6	22	2.86	1,2
	Cr 0.25			20% Al_2O_3	359	379	2.1	98.6	21.5	2.94	1,2
				13% SiC	317	356	4.9	89.5	17.9	—	1
				20% SiC	440	585	4.0	120.0	—	—	3
				30% SiC	570	795	2.0	140.0	—	—	3
2014A	Cu 4.4	Extrusion	T6	Nil	414	483	13.0	73.1	25.3	2.80	1,2
	Mg 0.7			10% Al_2O_3	483	517	3.3	84.1	18.0	2.92	1,2
	Si 0.8			15% Al_2O_3	476	503	2.3	91.7	18.8	2.97	1,2
	Mn 0.75			20% Al_2O_3	483	503	0.9	101.4	—	2.98	1,2
				10% SiC	457	508	1.8	91.2	17.7	—	1
		Sheet	T6	8.2% SiC	448	516	4.5	82.5	—	—	1
2219	Cu 6.0	Extrusion	T6	Nil	290	414	10.0	73.1	—	—	1,2
	Mn 0.3			15% Al_2O_3	359	428	3.8	88.3	—	—	1,2
	V 0.1			20% Al_2O_3	359	421	3.1	91.7	—	—	1,2
2618	Cu 2.0	Sheet	T6	~10% SiC	396	468	3.3	93.6		—	1,6
	Mg 1.5	Extrusion	T6	Nil	320	400	—	75.0	—	—	1,6
	Si 0.9	Extrusion	T6	13% SiC	333	450	6.0	89.0	28.9	—	1,6
	Fe 0.9										
	Ni 1.0										
7075	Zn 5.6	Extrusion	T6	Nil	617	659	11.3	71.1	—	—	6
	Mg 2.2			12% SiC	597	646	2.6	92.2	—	—	6
	Cu 1.5										
	Cr 0.2										
8090	Li 2.5	Extrusion (18 mm)	T6	Nil	480	550	5.0	79.5	—	—	1,6
	Cu 1.3		T6	12% SiC	486	529	2.6	100.1	—	—	1,6
	Mg 0.95										
	Zr 0.1										

Table 37.4 MECHANICAL PROPERTIES OF ALUMINIUM ALLOY COMPOSITES AT ELEVATED TEMPERATURES

Base Alloy	*Nominal composition*	*Form*	*Heat treatment*	*% particulate*	*Temperature* °C	*0.2% proof stress* MPa	*Tensile strength* MPa	*References*
6061	Mg 1.0	Extrusion	T6	15% Al_2O_3	22	317	359	1
	Si 0.6			15% Al_2O_3	93	290	331	1
	Cu 0.2			15% Al_2O_3	150	269	303	1
	Cr 0.25			15% Al_2O_3	204	241	262	1
				15% Al_2O_3	260	172	179	1
				15% Al_2O_3	316	110	117	1
				15% Al_2O_3	371	62	69	1
2014A	Cu 4.4	Extrusion	T6	15% Al_2O_3	22	476 (413)	503 (483)	1
	Mg 0.7			15% Al_2O_3	93	455 (393)	490 (434)	1
	Si 0.8			15% Al_2O_3	150	407 (352)	434 (379)	1
	Mn 0.75			15% Al_2O_3	204	317 (283)	338 (310)	1
				15% Al_2O_3	260	200 (159)	214 (172)	1
				15% Al_2O_3	316	103 (62)	110 (76)	1
				15% Al_2O_3	371	55 (35)	55(41)	1

Figures in parentheses are for basic alloy without particulate.

Table 37.5 MECHANICAL PROPERTIES OF MAGNESIUM ALLOY COMPOSITES AT ROOM TEMPERATURE

Base Alloy	*Nominal composition*	*Form*	*% reinforcement*	*0.2% proof stress* MPa	*Tensile strength* MPa	*Elongation* %	*Elastic modulus* GPa	*References*
ZK60A	Mg–5.5Zn–0.5Zr	Extruded rod	Nil	260	325	15.0	44	5
			15% SiC(partic.)	330	420	4.7	68	5
			20% SiC(partic.)	370	455	3.9	74	5
			15% SiC(whisker)	450	570	2.0	83	5
			20% B_4C(partic.)	405	490	2.0	83	5
	MG–12Li	Squeeze infiltration	Nil	—	80	8.0	—	7
		Squeeze infiltration	12% Al_2O_3(fibre)	—	200	3.5	--	7
		Squeeze infiltration	24% Al_2O_3(fibre)	—	280	2.0	-	7
		Extruded rod	Nil	—	75	10.0	45	7
		Extruded rod	20% SiC(whisker)	—	338	0.8	112	7

Table 37.6 MECHANICAL PROPERTIES OF TITANIUM ALLOY COMPOSITES

Base Alloy	*Form*	*% particulate*	*Temperature* °C	0.2% *proof stress* MPa	*Tensile strength* MPa	*Elongation* %	*Elastic modulus* GPa	*References*
Ti–6Al–4V	Forging	10% TiC	21	800	806	1.13	106–120	4
		10% TiC	427	476 (393)	524 (510)	1.70 (11.6)	—	4
		10% TiC	538	414 (359)	455 (441)	2.40 (8.5)	—	4
		10% TiC	649	369 (221)	317 (310)	2.90 (4.2)	—	4
		10% B_4C	21	—	1055 (890)	—	205	5

Figures in parentheses are for basic alloy without particulate.

Table 37.7 MECHANICAL PROPERTIES OF ZINC ALLOY COMPOSITES AT ROOM TEMPERATURE

Base Alloy		*Nominal composition*	*Form*	*Tensile strength* MPa	*Elongation* %	*Elastic modulus* GPa	*References*
ZA–12	Zn–12%Al	As cast	Nil	300	5	87	8
		As rolled	Nil	350	22	115	8
			10% SiC	323	0	119	8
			20% SiC	373	0	129	8
		Extruded	Nil	313	—	102	8
			20% Al_2O_3	532	—	120	8
ZA–27	Zn–27%Al	As cast	Nil	410	2	73	8
			10% SiC	396	0	92	8
			20% SiC	330	0	110	8
			50% SiC	310	0	220	8
		As rolled	Nil	393	16	85	8
			10% SiC	370	3	89	8
			20% SiC	349	0	102	8
		Extruded	Nil	340	—	83	8
			12% SiC	382	—	105	8
			16% SiC	466	—	130	8
			Nil	314	—	78	8
			20% Al_2O_3	382	—	100	8

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